NASA/TM—97-206323

Design, Installation, and Evaluation of an Altitude Test Facility Modification

Mahmood Abdelwahab, Allan S. Moore, Ronald H. Soeder,
Richard N. Sorge, and Richard DelRoso
Lewis Research Center, Cleveland, Ohio

Dennis J. Dicki
DYNACS, Inc., Brook Park, Ohio

November 1998

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DESIGN, INSTALLATION, AND EVALUATION OF AN ALTITUDE TEST FACILITY MODIFICATION

Mahmood Abdelwahab, Allan S. Moore, Ronald H. Soeder,
Richard N. Sorge, and Richard Del Roso
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Dennis J. Dicki
DYNACS, Inc.
Brook Park, Ohio 44141

SUMMARY

This report describes the design, installation, and evaluation of the turbine engine altitude test facility modifications. This facility is located in test cell 4 (PSL4) at the Lewis Research Center Propulsion Systems Laboratory (PSL). The modifications were made to enhance the test cell capability for engine inlet air supply conditions from a prior maximum of 55 psia and 600 °F to a new rating of 165 psia and 1200 °F. The maximum conditions reached during the interim evaluation were 129 psia and 844 °F at an airflow of 159 lb/sec. Also, the modified facility airflow quality as defined by the flow characteristics at a typical gas turbine engine inlet were investigated and were adequate.

INTRODUCTION

This report documents the design, installation, and evaluation of modifications made to the NASA Lewis Research Center Propulsion Systems Laboratory test cell 4 (PSL4) to allow it to supply combustion air at a rating of 165 psia and 1200 °F. The major modification was the installation of a new water-cooled insert in the existing test chamber inlet plenum. After the modifications were completed, all possible operating configurations were used in several tests conducted to verify the design criteria and to validate the facility airflow qualities.

In the late 1980's, it became evident to the Lewis Research Center management that the aeronautics mission required engine test facilities that could provide high-pressure and high-temperature air to simulate high Mach numbers. At that time, Lewis had two active, full-scale, aircraft turbine engine altitude test chambers (designated PSL3 and PSL4) that were first operational in 1972. The test chambers simulate aircraft flight conditions for a turbine engine mounted in a fixed position in the test section of the chamber. Air flows through the chamber inlet plenum to the engine inlet at the stagnation pressures and temperatures that match the altitude and Mach number of desired flight conditions. In these test chambers, flight conditions that can be simulated range from near sea level to a 70 000-ft altitude with forward velocities up to Mach 3.0. To meet the new requirements of higher Mach numbers, PSL4 was chosen for the modifications because in its existing configuration, it presented fewer mechanical problems than PSL3. The main modification was the addition of a water-cooled insert to the inlet plenum to allow higher pressures and temperatures. Predicated on the aeronautical mission at the time and based on existing PSL service equipment (combustion air and exhaust), design values, and assumed test article geometry, the following test program scenarios were considered in formulating the design criteria for the modification:

Test article	Capability		
	Pressure, psia	Temperature, °F	Airflow, lb/sec
Supersonic free-jet nozzle	165	1200	280
Turbine engine gas generator (core engines)	165	800	380
High-Mach-number turbine engines	165	800	380
Hypersonic direct-connect rig	165	600	100
Current turbine engine	60	600	400

Design changes were initiated in December 1990 with fabrication and installation completed in February 1993. To evaluate the success of the design and to determine the airflow quality of the modified PSL4, this report will discuss the design criteria, describe the modification, and then present data collected from several articles that were tested in the facility between 1993 and 1996. These articles were a low-temperature, Lewis-designed ASME nozzle, a high-temperature, Lewis-designed nozzle using Supersonic Tunnel Association (STA) coordinates, and a turbofan engine. All possible facility configurations were employed. Data were collected over a range of inlet temperatures from −50 to 884 °F and pressures from >1 to 129 psia.

PROPULSION SYSTEMS LABORATORY MODIFICATIONS

Propulsion Systems Laboratory

The NASA Lewis PSL complex (fig. 1) consists of the laboratory building, the equipment building and its control building, the combustion air heating and refrigeration building, and a cooling water tower system (not shown in the figure).

The PSL building has two altitude test chambers (PSL3 and PSL4) connected to the central equipment building (described next) through an exhaust plenum chamber and a combustion air supply pipe system. Included in the PSL building are a data room that houses the local data processing equipment, a control room for facility and/or engine operation, and a shop area. Each chamber test section is 38 ft long and 24 ft in diameter and is concentric with respect to its exhaust and inlet sections. The distance from the exhaust plenum chamber centerline to the test section floor for PSL3 and PSL4 is 6 and 4 ft, respectively. Both chambers share one common air pressure control station, one exhaust plenum chamber, one exhaust altitude control system, and an isolation valve (davit valve) used to block the exhaust equipment from the inactive test chamber (only one chamber can be active during testing). The exhaust plenum chamber consists of a water-cooled heat exchanger (referred to as primary cooler), a water spray cooler (referred to as spray cooler), and a de-mister, all for the purpose of reducing engine exhaust to the operating limit of the exhaust machinery (~150 °F). The altitude and inlet air pressure control valves are hydraulic with the position controlled by servoamplifiers through the facility computerized control system. A torus manifold at the upstream end of each test section supplies cooling air to keep the temperature below the operating limit of the test section (~150 °F). The bypass valve system is used primarily during fast engine acceleration or deceleration to keep the engine inlet pressure and temperature constant while the airflow changes. It consists of two (48- and 24-in.-diam) valves with the inlet located in the inlet plenum of each chamber and the discharge at the exhaust plenum.

The equipment building contains the combustion air supply and the drying and exhaust machinery shown schematically in figure 2. With this equipment, several combinations and routing arrangements are possible, resulting in a multitude of combustion air pressures and flow rates that can be delivered to several other facilities at Lewis. Figure 3 schematically shows the nominal piping and valve system of PSL, its tie-in to the equipment and the heating and refrigeration buildings, and the nominal capabilities of the main components.

The combustion air heating and refrigeration building is located adjacent to the engine test building and is shown schematically in figure 3 with the nominal size and operating conditions for its associated piping and valve systems. The building houses three air turboexpanders for refrigeration and two heat exchangers for heating. The expansion turbine operation requires the use of one or both of the available desiccant air dryers and the high-pressure air supply (165 psia). Heated air is supplied to the facility through the heat exchanger system (fig. 4(a)) consisting of air intake and discharge headers, a heat exchanger, an exhaust silencer, and a hot gas supply system. The heat exchanger (fig. 4(b)) is a counterflow shell and tube configuration containing a bundle of 637 30.0-ft-long tubes (1.5-in. outside diam; 083-in.-thick wall) installed using a 52.25-in.-inside-diameter shell. The hot gas system consists of a J57 gas turbine engine and its afterburner system (fig. 4(c)). While the ambient-temperature combustion air enters the intake header, passes over the tube bundle, and exits into the discharge header as nonvitiated air, the exhaust products from the J57 turbine engine pass inside the tubes and exit through the exhaust silencer. The heat exchanger system was installed in 1972, but the augmentor system had never been operated until the plenum insert modification was made to PSL4. Each exchanger has a set of temperature rakes installed at the inlet to monitor the temperature profiles. Reference 1 provides a more indepth discussion of this heat exchanger system design (used at another NASA Lewis facility).

The cooling tower water (fig. 5(a)) system consists of cooling tower pumps, spray pumps, return pumps, and auto- and manual control valves. This system uses softened and chemically treated water to prevent scale and corrosion and supplies processed water at a nominal capacity of 100 000 gal/min to the combustion air line, inlet plenum, exhaust plenum water-cooled heat exchanger, and spray cooler receiver tank. A separate water system is used for the spray cooler (fig. 5b).

Capabilities.—The nominal capabilities of the combustion air, exhaust, and drying machinery are shown in figure 2 and those of PSL are shown in table I. For some items in the table, the full capabilities cannot be achieved because of the constraints imposed by the air supply and exhaust systems (combustion air inlet temperature, amount of cooling water in the exhaust system, airflow, etc.). The following information takes these into account and represents the net capabilities of the overall system as they relate to PSL. The tabulated total airflow from the equipment building is not simultaneously available because shared equipment limits the airflow available at any given pressure level. For example, the output of each of the four low-pressure compressors that supply low-pressure air (55 psia) to PSL is 120 lb/sec (fig. 2). This air is compressed to higher pressure levels (165 psia) by serially staging low-pressure with high-pressure compressors in various combinations. Two high-pressure compressors are available, each putting out 190 lb/sec. Water coolers are used to reduce this compressed air temperature to the range of 90 to 60 °F. Airflows at temperatures down to approximately 45 °F are achieved by passing air from the low-pressure compressors through dehydrators, from which the total capacity of the flow is about 475 lb/sec. The desiccant dryers further dry the dehydrated air to a dewpoint of approximately −40 °F, which is required for turboexpander operation. The exhaust system gas flow capacity depends on altitude. The required mass flow-altitude conditions are achieved by the 27 available compressor casings in up to seven stages that can handle up to approximately 750 lb/sec at near sea level and up to 28 lb/sec at a 70 000-ft simulation.

Ambient air from the equipment building is conditioned to the proper temperature by passing through the heating and refrigeration building (fig. 3). When higher temperatures are required, the air is routed through the two heat exchangers where a maximum of 240 lb/sec can be nominally heated to 600 and 1200 °F (at the heat exchanger exit) if the afterburner system is activated. In turn, this heated air can be blended with the lower temperature air (from IV–6 in fig. 3) to achieve intermediate air temperatures at flows up to 480 lb/sec. When lower temperatures are required, air from the low-pressure compression system is routed through the desiccant dryers, the high-pressure compression system, and then the turboexpanders where it is expanded to 10 psia or lower. The combined nominal capacity of the three expansion turbines is 380 lb/sec at −90 °F (at the turpoexpander exit). The delivered hot and cold air to the facility inlet is approximately 1100 °F and −50 °F, respectively. The PSL hot and cold piping temperature limits are 1200 and −50 °F (see fig. 3).

Other systems that support this facility are the liquid fuel and special fuel, industrial waste, gaseous nitrogen, hydraulic (3000 psia at 50 gal/min), gaseous hydrogen (2.75 lb/sec at 1000 psia), gaseous oxygen (10 lb/sec at 300 psia), high-pressure air (76 lb/sec at 450 psig), and shop air (10 lb/sec at 150 psia).

Operation.—A normal gas turbine engine installation consists of mounting the engine on a thrust frame fixed to the test section floor. The engine inlet is connected directly to the inlet air supply system through piping and a bellmouth with a sealing arrangement to isolate the inlet from the engine. Engine exhaust is directed to the exhaust section through piping designed to accommodate the total flow (engine exhaust and facility cooling air). Combustion air and exhaust supply valves are hydraulically operated and controlled with a Westinghouse electronic system that is also used to control all other PSL services.

Description of Original PSL4 Inlet Plenum

The original inlet plenum system for PSL4 is shown schematically and in detail in figures 6(a) and (b), respectively. As seen in figure 6(a), the plenum has a stepped configuration in which the conditioned air inlet is upstream of the atmospheric air inlets. Located about one inlet plenum diameter downstream of the conditioned air inlet is the bulkhead separating the inlet plenum from the test section. Also indicated are the approximate locations of typical inlet duct/engine installations. The response time of the air supply system is too slow for the system to follow rapid engine transients. Therefore, rapid changes in engine airflow requirements are handled by bypassing varying amounts of air around the altitude chamber through a pipe fitted with coarse and fine high-response valves. The bypass pipe exits the plenum just upstream of the altitude chamber bulkhead and discharges into the exhaust plenum. An annular liner was installed in the plenum at the bypass duct penetration to minimize flow distortion when the test cell bypass valves are in operation (fig. 6(b)).

Three flow-straightening wire-cloth panels of various meshes and one honeycomb structure (3- by 3-in. cell openings) were installed in the plenum duct to enhance flow distribution quality. The scroll (T-) located at the upstream entrance to the inlet plenum structure was designed and rated for the combustion air service criteria of 165 psia and 1200 °F. The combustion air line upstream of this section is rated for these service criteria all the way back to the heat exchanger system discharge valve (AC4663, fig. 3). The air line piping and scroll section are fabricated from carbon steel. The combustion air pipeline between the 84-in. exit and the heat exchanger exit is water cooled (fig. 3) and internally thermally insulated with a stainless-steel-sheet-sandwich panel system. The deliverable combustion air temperature to the inlet of the plenum insert is limited to approximately 1050 to 1100 °F, even though 1200 °F is delivered at the exit of the heat exchanger through valve AC4663. Uninsulated portions of the combustion air line and losses through the internal insulation contribute to this temperature loss.

Design Criteria and Description of PSL4 Modification

Inlet plenum design modification criteria.—To meet the requirements, it was proposed that a new water-cooled insert be installed in the plenum. The following criteria were established for the inlet plenum design modification:

1. The new structure, designed to meet the 165 psia and 1200 °F service requirements, must fit in the existing plenum structure.
2. The demolition of the existing plenum structure must be limited to the modification of the plenum/test chamber bulkhead and the removal of the existing flow-conditioning hardware.
3. Bypass flow control for combustion air must be required for the new plenum insert.
4. Thermal losses must be minimized through the new plenum insert wall.
5. A provision must be made for introducing atmospheric inlet air to the new plenum insert. An inspection manway is also required at the downstream end of the plenum insert.
6. Provisions for enhancing the flow quality conditioning must be required for combustion air delivered to the test article located in the test chamber.
7. The pressure and temperature limits for the existing plenum structure and the test chamber bypass system must not be exceeded (60 psia and 600 °F) as a result of any operational procedure.
8. The design goal of a 50-ft/sec combustion air velocity must be established at the plenum insert exit plane (ref. 2).
9. The added pressure loading from the plenum insert (165 psia) must not exceed the overall allowable thrust load on the facility anchor points.
10. Provisions must be made in the insert to accommodate the addition of a gaseous hydrogen burner to be added at a later date.

Inlet plenum modification description.—The final configuration is shown schematically in figures 7(a) and (b). Figure 7(c) is a photograph of the assembled insert before its installation in the plenum. The modified PSL4 plenum consisted of a combustion air system isolation bulkhead, a plenum insert settling chamber comprising two cylindrical sections and a conical diffuser section, a plenum insert combustion air bypass control system, a combustion airflow-conditioning section, and a modification of the plenum-test chamber isolation bulkhead. Salient features of the major components are described as follows:

Combustion air isolation bulkhead: The combustion air isolation bulkhead was installed on an existing flange located at the upstream end of the inlet plenum structure. This bulkhead isolates the combustion air (165 psia and 1200 °F) from the existing plenum pressure vessel (rated at 60 psia and 600 °F). The internal diameter of this bulkhead also provides structural support for the upstream end of the new plenum insert and allows some axial thermal expansion of the plenum insert relative to the plenum using an inflatable seal arrangement. The bulkhead is water cooled and is fabricated from carbon steel.

Plenum insert (settling chamber): The plenum insert chamber consists of three water-cooled flanged spool pieces, two cylindrical and one conical diffuser, that have internal thermal insulation panels ("shingles") installed. They are constructed of carbon steel and are rated for 165 psia and 1200 °F. The overall assembly length is 30.33 ft. The upstream spool piece (75.0-in. inside diameter) has a 24-in.-diameter bypass duct connection and four 30-in.-diameter manways that if opened can be used to allow atmospheric air into the insert or as additional combustion air bypass discharges. The conical diffuser section allows the air to expand from a 75.0- to a 107.7-in. diameter at a

7.5° half-angle. The exit spool piece (107.7-in. inside diameter) has one inspection manway. The plenum insert assembly is supported at the downstream end by the plenum-test chamber bulkhead through a bolting arrangement and at the upstream end by spring hangers, with the combustion air isolation bulkhead acting as a guide.

Plenum insert bypass: The plenum insert bypass control system consists of one 24-in. butterfly valve and one 8-in. butterfly valve acting as a vernier bypass for the 24-in. valve. The 24-in.-diameter discharge from these valves is directed into the 48-in.-diameter test chamber plenum bypass line. The bypass inlet connection is made at the plenum insert upstream spool piece section.

Insert flow conditioning: The flow-conditioning section consists of two 316 stainless-steel perforated plates (60-percent open area) located 10 in. apart. Downstream of these is located a honeycomb section consisting of hexagonal cells □ by 3.0 in. long, with a 96.5-percent open area. The honeycomb section is fabricated from 316 stainless steel.

Test section isolation bulkhead: An uncooled, carbon steel, conical bulkhead separates the test chamber from the original plenum structure. This bulkhead also supports the downstream end of the plenum insert. The original plenum bulkhead structure had to be modified to allow the installation of the combustion air isolation bulkhead. As a result of this final design, the following limitations were introduced to the original test program scenarios given in the Introduction:

1. Supersonic free-jet nozzle: Close new insert bypass valves and manways and limit the original plenum bypass flow (from atmospheric intakes) to 100 lb/sec when operating at altitudes above 60 000 ft because of exhaust machinery limits.
2. Turbine engine gas generator (core engines):
   - (a) Limit cooled air to −50 °F because of facility piping temperature limits.
   - (b) Limit bypass flow through new and existing line to 370 lb/sec at 600 °F.
   - (c) Limit new bypass to 340 lb/sec at 70 psia and 800 °F.
3. High-Mach-number turbine engines:
   - (a) Limit cooled air to −50 °F because of facility piping temperature limits.
   - (b) Limit bypass flow through new and existing line to 370 lb/sec at 600 °F.
   - (c) Limit new bypass to 340 lb/sec at 70 psia and 800 °F.
4. Hypersonic direct-connect rig: Limit new bypass flow to 73 lb/sec at 150 psia and 600 °F.
5. Existing turbine engine:
   - (a) Limit cooled air to −50 °F because of facility piping temperature limits.
   - (b) Use the 30-in. insert manways in the open configuration for high flow transients when using 55-psia combustion air supply because of the flow limitation of the smaller insert bypass system.
   - (c) Operate with insert manways open when using atmospheric air.

Installation description.—Extensive demolition was involved in this construction. The test chamber main thrust bed (serves as the test chamber floor) and the test chamber cooling air torus had to be removed and set aside. The original plenum flow-conditioning system and the bypass line annular shield were removed and scrapped. The original plenum-test chamber bulkhead opening was increased to permit the installation of the high-pressure isolation bulkhead located at the plenum inlet.

A new flange was welded to the modified plenum-test chamber bulkhead. The combustion air isolation bulkhead was installed at the upstream end of the existing plenum, followed by the three prefabricated pressure vessels. A conical transition bulkhead then supported the exit end of the plenum insert to the plenum-test chamber bulkhead. Spring hangers supported the upstream end of the plenum insert. The plenum insert bypass system was then installed. The internal insulating panels (shingles) were installed onsite after the plenum insert was installed. The flow-conditioning hardware was the final system to be installed onsite.

The test chamber main thrust bed was then reinstalled 6 ft. below at the test cell axial centerline (previously 4 ft. below at the axial centerline). This necessitated an extensive modification of the piping in the test chamber. Also, the thrust bed was modified to permit the installation of a torque isolation structure (see the section Multicomponent thrust measurement system). The cooling air torus was also reinstalled.

TEST APPARATUS

The inlet plenum modification required an evaluation after the installation was completed. The criteria to be evaluated were the system mechanical integrity when it was subjected to the new pressure and temperature limits;

the quality of the delivered combustion airflow; and the test envelope available with the modified inlet plenum. The approach taken to perform the evaluation included these procedures: (1) test articles were to be chosen to minimize the cost and reduce the risk to the article and the facility; (2) the flow quality at the insert exit was to be verified at low pressures and temperatures to allow the facility to come online for tests that required only low pressure and temperature (60 psia and 600 °F); (3) the aeronautical budget process was to be used to advocate for tests that required new hardware (165 psia and 1200 °F); (4) tests were to piggyback other experiments to complete or enhance the collected data. Based on this approach, evaluation data were collected between 1993 and 1996 using these test articles:

1. Cold-pipe nozzle systems (specific to the evaluation) were used to evaluate the test envelope available for in-service turbine engines and to evaluate the combustion airflow quality that would be delivered to a turbine engine at low pressure and temperature (55 psia and 600 °F).
2. Hot-pipe nozzle systems (specific to the evaluation) were used to evaluate the test envelope available to higher performance turbomachinery that would be required in the future and to evaluate the mechanical integrity of the facility when it was subjected to the upgraded temperature and pressure.
3. A turbofan engine system was used as the first scheduled test in PSL4 after the modification.

The hardware, instrumentation, and procedures used for each test article are described next.

Cold-Pipe System

This system used a 35.0-in.-inside-diameter carbon steel pipe that had the same inlet flange interface and engine mounting points as those of an F100 turbofan engine. The exhaust flange for this pipe interfaced with a typical F100 engine afterburner (K-flange). The cold-pipe support structure was mounted to a six-degrees-of-freedom, multiaxis, thrust measurement system module, which in turn was mounted to the test chamber floor. This thrust system is described in detail in references 3 and 4. Figures 8(a) and (b) show the cold-pipe installation in PSL4. An FOD (foreign object damage) screen assembly was installed upstream of the bellmouth for some of the cold-pipe tests.

Cold-pipe inlet system.—As shown in figure 8(b), the combustion air was directed from the plenum insert through a bellmouth (32.2-in. throat diam) and an airflow measurement spool piece (station 1.0). The inlet mass flow rate to the cold pipe was determined at this station by the method described in appendix 1 of reference 5. Downstream of the flow measurement station, the inlet duct was anchored to the test chamber floor (ground) during early tests. The inlet section between the duct anchor point and the cold pipe contained the inlet seal assembly, an instrumentation section (station 2.0), and a gimbal ring. The inlet seal assembly and the gimbal ring are used to compensate for radial misalignment between the duct and the cold pipe. The inlet seal assembly used an inflatable silicone rubber torus that was retained between the duct assembly and the station 2.0 spool piece (attached to the cold pipe). The inflatable seal provided radial misalignment adjustment, axial thermal growth compensation, and a metric thrust break for vectored thrust measurement.

Cold-pipe nozzle systems.—Several nozzles were used in the cold-pipe evaluation and were attached at the K-flange location:

1. An ASME nozzle (28.27-in.-diam throat, 628 $in.^2$) was used for most of the test program. In addition to a choke plate (595-$in.^2$ open area) that was used for some tests, canted ducts (7.5° and 15°) were used to divert the exhaust flow from axial by that amount. The canted ducts could be rotated manually by 45° increments about the axial centerline of the cold pipe. This was done to generate a vectored thrust to check out the six-degrees-of-freedom thrust measurement system. The choke plate and canted ducts were located upstream of the ASME nozzle. See figure 8(c) for the arrangement relative to the cold pipe.
2. An F100 engine augmentor nozzle, a convergent-divergent variable-area device, was remotely actuated to provide a variable airflow to evaluate the thrust system and the plenum bypass control dynamics. The nozzle area control was operated remotely and was disconnected from the normal engine fuel control, with shop air used as the operating fluid.
3. A conical nozzle (12.19-in.-diam throat, 117 $in.^2$), used for a facility acoustic test, provided low-range flow characteristics (fig. 8(c)).

4. An F–119 engine calibration and vectoring nozzle, used only in an axial mode, also provided a different flow range evaluation. Figure 8(d) shows the F–119 round nozzle installation in PSL4.

Multicomponent thrust measurement system.—The thrust measurement system was manufactured by Ormond, Inc. and was mounted to the test chamber main thrust bed with a three-point-suspension through a torque isolation structural adapter located at the chamber floor level. The adapter isolates the test article from any facility test-bed bending, torsional stresses, or deflections. The main thrust bed is locked out, thus acting as a thrust fixed point. Details of this system are given in references 3 and 4.

Airflow quality evaluation instrumentation.—During the cold-pipe testing, several instruments were used to evaluate the quality of the airflow being delivered to the test article from the modified inlet plenum. These devices were used in addition to various static instruments installed in the plenum insert (pressure and temperature) and the normal pressure and temperature rakes installed at stations 1.0 and 2.0 of the engine inlet duct. The devices are described as follows:

1. A total pressure and temperature rake was installed in the 84-in.-diameter combustion air header leading into the scroll section just upstream of the plenum insert entrance. Later in the test series, it was reinstalled in the 75.0-in.-diameter section of the plenum insert downstream of the plane containing the bypass and manway penetrations. The rake was installed here in either a 0 °-180 °, 157°-337°, or a 90°-270° orientation and used 23 total pressure and 6 total temperature sensors. The rake was used to detect any distortion levels at these two locations (84- and 75-in.-diam sections). At a future time, a gaseous-hydrogen-fueled heater system will have to be installed in the upstream section of the plenum insert to deliver 1200 °F combustion air to a test article (i.e., supersonic free jet). Therefore, this rake provided a way to measure the distortion level for later reference. Figure 9(a) shows the rake installation in the plenum insert duct.

2. A set of static pressure taps was installed axially from the entrance to the exit of the insert at several angular locations (fig. 9(b)). Static pressure measurements were made by laying 1/16-inch Prandtl tubes (open on the side and closed at the end) on the insert surface. The purpose of this instrumentation was to quickly identify any major flow anomaly in the new insert system.

3. A rotary total pressure rake was installed forward of the bellmouth inlet face in the plenum insert (fig. 9(c)). This rake was configured as a cross with probes on each arm on 12 centers of equal area based on a 6.0-ft diameter (60.0-in. bellmouth lip diam). The plane of the probe tips was 14.5 in. forward of the bellmouth face. The rake was remotely actuated at a rotational speed of 1 deg/sec and had a range of motion of ±45° from the nominal home position, thus assuring complete frontal coverage of the bellmouth face. This pressure survey was used to quantify the pressure distortion at various flow conditions.

4. A second rotary total pressure rake was installed in the cold-pipe inlet duct (fig. 9(d)). An existing rotating distortion screen holder was modified to carry a cross-shaped rake holding probes on each arm on six centers of equal area based on a 34.8-in. duct diameter. This device was remotely actuated with the same rotational speed and range of motion as the unit described in item 3. This pressure survey was used to quantify the pressure distortion of the delivered air to the face of the test article.

5. Station 1 (fig. 8(b)) boundary layer rakes were used to calculate mass airflow into the inlet of the pipe system. The rakes and the method of calculation are described in appendix 1 of reference 5.

6. Station 2 (fig. 8(b)) instrumentation consists of two temperature and two total pressure rakes, each containing two sensing elements.

Hot-Pipe System

A pipe section with a nozzle was installed in the test chamber to evaluate the high-pressure and temperature performance of the inlet plenum modification. The piping assembly (figs. 10(a) and (b)) was anchored to the plenum insert downstream bulkhead and was supported from the test chamber floor. The assembly was designed to permit axial growth due to thermal expansion. No provisions were made to measure axial thrust for this evaluation phase. All components of the hot-pipe assembly were rated for 165-psia and 1200 °F service and all sections were water cooled. With the exception of the conical spool piece, all the components were used in a previous program. A short description of each section from upstream to downstream follows:

1. A conical spool piece with a 45 ° half-angle provides adaptation from the plenum insert exit plane (107.7-in. diam) to a flow conditioner (40.0-in. diam). This section was fabricated from grade 516 carbon steel.

2. A flow conditioner composed of two spool pieces (60.0 in. long with a 40.0-in. inside diam) was fabricated from 304 stainless steel.

3. An elliptical bellmouth section with a 13.0-in.-diameter throat was fabricated from 17–4 PH stainless steel.

4. An instrumentation spool piece at station 2.0 (26.0 in. long with a 13.0-in.-inside diam) provides ports for eight rakes at a measurement plane one diameter downstream of the bellmouth throat. This spool piece was fabricated from 17–4 PH stainless steel.

5. The exit nozzle has a 10.31-in.-diameter throat and was designed with STA (Supersonic Tunnel Association) coordinates. The nozzle diverges from a 13.0-in. diameter to a 14.75-in. diameter prior to entering the throat. Instrumentation station 7.0 has two rake ports installed in the 14.75-in.-diameter section of the nozzle. The nozzle was fabricated from 17–4 PH stainless steel.

TEST MATRIX

As mentioned in the Introduction, data were collected from several test articles between 1993 and 1996. Several facility configurations were employed. The following table summarizes the test matrix in terms of the test article nozzle system, facility configuration, and test conditions:

Nozzle configuration	Facility configuration	Test conditions
Cold pipe (ASME)	1. Insert bypass and manways closed; plenum bypass and atmospheric ports open or closed (for all test program scenarios) 2. Insert bypass open and manways closed; plenum bypass open and atmospheric ports closed (for all test program scenarios) 3. Insert bypass closed and manways open; plenum bypass open and atmospheric ports closed (for all test program scenarios including high flow transients) 4. Insert bypass closed and manways open; plenum bypass closed and atmospheric ports open (for all test program scenarios if atmospheric air is needed)	Insert exit temperature range, –50 to 600 °F Insert exit pressure range, <1 to 33 psia
Hot pipe (STA)	1. Insert bypass and manways closed; plenum bypass and atmospheric ports open 2. Insert bypass open and manways closed; plenum bypass and atmospheric ports open.	Temperature range, 60 to 884 °F Pressure, 3 to 133 psia
Turbofan engine	1. Insert bypass and manways closed; plenum bypass open and atmospheric ports closed 2. Insert bypass open and manways closed; plenum bypass open and atmospheric ports closed 3. Insert bypass closed and insert manways open; plenum bypass closed and atmospheric ports open (atmospheric air)	Temperature, –50 to 130 °F Pressure, 0.5 to 15 psia

DISCUSSION OF RESULTS

The results are presented in terms of the system mechanical integrity, delivered airflow quality, and test scenarios performed with the modified inlet plenum. The mechanical integrity discussion includes items that failed during the test and the corrected action taken. The flow quality discussion presents data to show the flow characteristics of (1) the new insert at several locations, (2) the flow quality at a typical gas turbine inlet, and (3) a comparison of the airflow and thrust of the modified facility and that of the manufacturer's facility using the same turbofan engine. Finally, the facility capabilities are discussed in terms of the test scenarios with the new modification.

System Mechanical Integrity

Plenum insert to isolation bulkhead seal.—An elastomeric, water-inflatable (200-psia) seal, installed between the plenum insert inlet section and the isolation bulkhead (fig. 11(a)), failed during cold-pipe tests. This seal prevents hot, high-pressure combustion air from entering the original inlet plenum structure (limited to 55 psia and 600 °F) and provides some limited axial thermal expansion. The original seal consisted of a solid rectangular silicone rubber cross section bonded to a rectangular silicone rubber tube, which had a water supply and return connections bonded to it. These connections were a constant source of mechanical failure. Also, the seal surface was charred by the combustion air supply at temperatures lower than 600 °F. Two actions were taken to correct these deficiencies:

1. A new seal configuration was procured from an alternate vendor. This three-piece design uses two solid rubber sections with the water-cooled tube radially inserted (not bonded) between the sections. The mechanical design (fig. 11(b)) for the water supply and the return connections is superior to the previous design. An alternate elastomer (EPDM) was selected for superior wear characteristics although it has a lower service temperature than that of silicone rubber.
2. In the original design, three surfaces of the seal cavity were water cooled, but the fourth surface (seal air deflector) was not. To enhance seal life, water-cooling provisions were made by bonding square aluminum alloy tubes (fig. 11(c)) to the outside diameter of the seal air deflector mounting flange. The tubes were bonded with thermally conductive epoxy. The cooling water for the tubes was manifolded from the isolation bulkhead cooling water supply and return.

After these modifications were completed, the facility was supplied with combustion air at 133 psia and 868 °F. The modifications appear to have been satisfactory.

Plenum insert flow-conditioning system.—Damage was incurred by the insert flow-conditioning system hardware during high-temperature operation. The perforated plate sections were axially bowed. The honeycomb flow-straightener support ribs and panels were laterally buckled, and some panels were locally separated from the ribs. Examples of the buckling are shown in figures 12(a) and (b). Further investigation revealed that radial thermal expansion provisions were inadequate for the damaged components. The supporting structures for the components were water cooled, but the components themselves could approach the combustion air temperatures. The plenum insert structure that supports the honeycomb assembly was modified to allow radial thermal expansion of the honeycomb assembly. The perforated plate structure, though bowed, showed no structural failure. The ring holes of the perforated plate section mounting were elongated to permit radial thermal expansion. This section was used for the subsequent tests and no plans have been made for its replacement. A replacement honeycomb flow straightener is being fabricated and will be installed when the schedule permits. As an interim measure, the existing straightener was repaired by reattaching the honeycomb panels to the ribs at locations where they separated. This repaired straightener was load-tested and reinstalled. It was successfully used for subsequent turbofan engine tests with the combustion air supply at 70 lb/sec, 15 psia, and −50 to 150 °F. It is safe to use the existing straightener at higher flows and pressures, but the replacement will be installed prior to operating at temperatures above 200 °F.

Facility heat exchanger system. —The facility heat exchanger afterburner was used for the first time to increase the combustion air supply to temperatures above the 600 °F previously achieved without the afterburner. No part of the heat exchanger system failed during testing; however, using the available information on its operating limits (see the following table), the system failed to produce the desired combustion air temperature at the insert exit (between 1050 and 1100 °F).

Tubeside	
Gas (J57 exhaust) temperature, °F	1250
Gas temperature difference between maximum and minimum, °F	200
Gas pressure, psia	165
Shellside	
Combustion air temperature, °F	1200
Combustion air pressure, psia	165

The operating limits reached during the hot-pipe tests are shown in figures 13(a) and (b), which present the heat exchanger inlet temperature profiles at two combustion air inlet airflows. These limits resulted in a maximum temperature of 868 °F at the insert exit at 78.9 lb/sec and 844 °F at 159 lb/sec, respectively. Because the available information did not clarify the location of the operating limits (tubeside, shellside, or both), no attempt was made to exceed the limits (increasing tube side gas temperature) during this test, but the following actions were taken:

1. An ASME Section VIII, Division 1 evaluation of the heat exchanger was performed. The results indicated that the heat exchanger was capable of a maximum tubeside (engine exhaust) inlet temperature of 1500 °F and pressure of 30 psia, provided that the cold shellside air is flowing prior to subjecting the exchanger to the 1500 °F exhaust gas. Based on a calculated heat transfer coefficient of 19.187 Btu/hr-ft^2-°F, the evaluation showed that the shellside air temperature reached 1190 °F. These results agree with another identical heat exchanger at Lewis that is already operating at the elevated temperatures. The ASME code includes some criteria for heat exchangers but gives no detailed approach for design. Because the heat exchanger has to meet these criteria at Lewis, the intent of the code was followed to the most practical extent for the evaluation. The results also indicated that the tube-to-tube sheet joints, the shell expansion joint, and the attachment welds were acceptable at the maximum operating conditions.
2. As seen in figures 13(a) and (b), the exchanger inlet temperature profiles indicate a low temperature at the inlet center, resulting in a difference of 200 °F between the maximum and the minimum. Based on experience with the same type of exchanger, the temperature difference was determined to be unacceptable because of possible stress problems with the tube sheet joints. To reduce the difference between the maximum and the minimum, the afterburner will be modified to allow independent control of the fuel supply pressure to each ring.

The belief was that taking these two actions would allow the heat exchanger to operate at inlet temperatures as high as 1500 °F, which should result in a combustion air temperature of approximately 1100 °F at the insert exit.

Flow Characteristics

After the installation of the new water-cooled insert, a major question was whether the airflow characteristics of the new modified facility configuration remained adequate or changed. This question is answered by presenting the flow quality data in terms of (1) pressure profiles at the combustion air inlet to the insert; (2) axial insert pressure profiles; (3) insert diffuser exit total pressure profiles; (4) insert exit pressure distortion levels; (5) typical engine inlet pressure distortion and two-dimensional CFD (computational fluid dynamics) results; and (6) a comparison of the airflow and thrust of this facility and a manufacturer's facility using the same turbofan engine.

Combustion air inlet header pressure profiles.—As stated in the section Airflow quality evaluation instrumentation, a total pressure rake was installed in the 84-in.-diameter combustion air inlet header at position 0°-180° (forward looking aft and down). The rake was mounted on an existing flange (71.5-in. inside diam) within the combustion air line pipe. Data were collected only for two facility configurations because of the test time and the need to change the location of the rake to the insert diffuser inlet where pressure profiles were deemed more important. The two facility configurations were the plenum insert bypass closed and then open with the plenum insert manways and atmospheric ports closed. The profiles are presented in figure 14. As seen from the data, the pressure outside the boundary layer increased from 22.4 to 22.6 psia (insert bypass closed) and from 24.9 to 25.2 psia (insert bypass open). This information was considered useful for any accurate, detailed CFD code analysis of the total insert system if a situation requiring it occurred at a later time.

Insert axial pressure profiles.—Static pressure probes were installed along the insert bottom and top inside-diameter surface (fig. 9(b)). The main purpose of this instrumentation was to detect any large distortion of the flow along the insert axis. Figures 15(a) to (d) present low-pressure and temperature data showing the axial pressure distribution from the entrance of the insert to the exit for several facility configurations representing the test program scenarios stated previously. In all four figures, the pressure difference between the bottom and top of the insert shows differences due to (1) the effect of the undeveloped flow (with possible flow reversal at the bottom) at the entrance to the insert; (2) the state of the plenum insert bypass, plenum insert manways, plenum bypass, plenum atmospheric ports (open or closed); and (3) the effect of the air conditioning devices. However, in all instances, the differences at the exit to the insert were minimum, which indicates the flow developing into one dimensional. In general, these data indicate no large, unexplained flow anomalies attributed to the new facility modifications for any of the proposed configurations.

Insert diffuser inlet pressure profiles.—The diffuser inlet is the location where a heater can be added to produce the desired 1200 °F temperature. Checking the total pressure profile will help in designing a heater system at this location. The total pressure rake installed in the combustion air inlet pipe was removed and installed in the insert diffuser inlet section (88 in. from the insert inlet) at several angular locations (0°-180° and 157°-337° as viewed forward looking aft) during several different tests with both the cold-pipe and hot-pipe systems. Figures 16(a) to (d) present data for several facility configurations and test conditions and indicate that a maximum pressure difference of 0.2 psia, existed along the diameter of the insert.

Plenum insert exit total pressure profiles.—The most important indicator of the airflow quality after the modification was the flow characteristics at the exit of the insert (entrance to a test article). Because of reduced resources, only flow uniformity had to be determined. This decision was based on a reasonable assumption of one-dimensional flow at the exit, prior experience, and a limited two-dimensional CFD code analysis. A rotating total pressure rake (discussed in the section Airflow quality evaluation instrumentation and shown in fig.10(c)) was installed at the entrance of a typical test article inlet bellmouth. The rotation mechanism was capable of changing the angular location of the rake in 1° increments for a motion range of ±45°. Figures 17(a) to (c) present bar plots of a pressure distortion parameter defined as

$$\frac{\text{Maximum pressure} - \text{average pressure}}{\text{Average pressure}}$$

for several facility configurations and test conditions during a total range of rotation of the rake of approximately 80° in increments of 5°. As seen from these figures, a maximum distortion level of about 0.6 percent was reached during operation using the plenum atmospheric-ports-open configuration (fig. 17(c)).

Reference 6 presents model data for the PSL4 original plenum configuration at its exit showing distortion levels in terms of the velocity spread between the maximum and minimum of 48 ft/sec for the plenum-bypass-closed configuration. For the modified plenum with the insert bypass closed, the distortion levels shown in figure 16(a) have a spread of approximately 85 ft/sec, assuming ideal one-dimensional flow.

Typical PSL inlet duct interface system performance.—The inlet duct interface system used with the cold-pipe tests consisted of an elliptical bellmouth with a ratio of 3:1 and a throat diameter of 32.2 in., a labyrinth seal duct, an airflow measuring duct, a gimbal duct, and other spool pieces (see fig. 8(b)). Further evaluation of the insert exit flow characteristics was conducted by (1) measuring the pressure distortion at the exit of a typical test article inlet duct interface system using the rotary total pressure rake described in the section Airflow quality evaluation instrumentation; (2) performing a two-dimensional CFD code analysis to verify the one dimensionality of the flow at the exit of the interface system; and (3) measuring the pitch and yaw angle at the exit of the interface at one location.

Pressure distortion data are presented in figures 18(a) to (c) for several facility configurations and flow levels. Based on these figures, the maximum level was 1.2 percent, which compares very well with previous F100 engine tests (for the same airflow) in PSL4 before the plenum modifications. That study employed an F100 engine in PSL4 before the plenum modifications and used the same inlet duct interface system.

A NASTAR CFD analysis of the flow characteristics was performed at a standard location in the inlet duct interface system where facility airflow to the test article is measured using boundary layer rakes and the assumption of one-dimensional uniform flow. The main objective of the analysis was to compare CFD boundary layer calculations with measured values and to ascertain the correctness of the one-dimensional flow assumption at the airflow measuring station. Figures 19(a) and (b) show the boundary layer total pressure profiles and the radial static pressure profiles for a test point where the inlet pressure, temperature, and flow were 11.4 psia, 60 °F, 160 lb/sec, respectively. As seen from these figures, the boundary layer profile is coincident with the CFD code values, and the maximum radial static pressure profiles did not exceed 0.02 percent. Both figures verify the validity of the facility airflow measurement methods and provide additional reasons to be confident of the airflow quality supplied by the insert to the test article inlet duct interface system.

Additional verification of the flow characteristics at station 1.0 were obtained by using a calibrated five-point probe to measure the pitch and yaw angles at a location 6 in. downstream of station 1 and at a radial location approximately 2 in. from the duct wall. At a Mach number of 0.47, the pitch and yaw angles were −1.7° and 0.9°, respectively.

First engine test in PSL4.—The first engine tested in the modified PSL4 was a two-spool turbofan engine with a class thrust level of 2300 lb. Figure 20 presents a portion of the engine performance data in terms of corrected net thrust versus corrected inlet airflow obtained at the manufacturer's sea-level static facility (circles) and at PSL4 (squares). The data for the two facilities show very close agreement, to within less than 0.5 percent, which further indicates the adequacy of the PSL4 flow characteristics after the modification.

Hot-pipe tests.—Figure 21 presents the insert exit temperature profiles during the hot-pipe tests. Figures 22 (a) and (b) present the hot-pipe total temperature and pressure profiles at station 2.0 (see fig. 10(b)). The data obtained during these tests are for the maximum pressure and temperature of 133 psia and 868 °F. These maximums do not represent the full capability of PSL4 because one of the high-pressure compressors in an equipment building was out of service during the hot-pipe testing. At the insert exit, the maximum difference in temperature was 10°. At station 2.0, this difference increased to 70° primarily because of the low temperature indicated by the probe closest to the hot-pipe, water-cooled wall. The pressure difference outside the boundary layer was less than 0.5 psia.

Test Scenarios With the Modified Plenum

The plenum modifications were based on the need at that time to accommodate the test program scenarios with requirements based on nominal equipment capabilities:

Test article	Capability		
	Pressure, psia	Temperature, °F	Airflow, lb/sec
Supersonic free-jet nozzle	165	1200	280
Turbine engine gas generator (core engines)	165	800	380
High-Mach-number turbine engines	165	800	380
Hypersonic direct-connect rig	165	600	100
Existing turbine engine	60	600	480

Based on the tests conducted during the evaluation of the modified PSL4, the following can be achieved in PSL4 utilizing only one of the high-pressure compressors in the equipment building:

Test article	Capability		
	Pressure, psia	Temperature, °F	Airflow, lb/sec
Supersonic free-jet nozzle	130	880	160
Turbine engine gas generator (core engines)	130	880	160
High-Mach-number turbine engines	130	800	160
Hypersonic direct-connect rig	129	600	100
Current turbine engine	60	600	480

CONCLUSIONS

The mechanical integrity of the modified test cell (PSL4) in the Propulsion Systems Laboratory was examined up to a pressure of 133 psia, a combustion air temperature of 844 °F, and an airflow of 159 lb/sec. After the modifications, the facility airflow quality was established to be satisfactory.

RECOMMENDATIONS

1. Independently vary the supply pressure to the afterburner fuel rings to modify the fuel spray system of the heat exchanger to produce more uniform temperature profiles at the inlet
2. Add a heater at the insert diffuser inlet (if necessary) to increase the temperature to 1200 °F.
3. Repeat the hot-pipe tests to verify all the recommended changes and to determine the full facility capabilities, integrity, and flow quality at the maximum design conditions.

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4. Precision Six-Component Thrust Measuring System for Aircraft Engine. Service Manual, MCT–90–122–50K, Ormond, Inc., Santa Fe Springs, CA, 1990.
5. Block, H.B., et al.: Techniques Utilized in the Simulated Altitude Testing of a 2D-CD Vectoring and Reversing Nozzle. NASA TM–100872, 1988.
6. Riddlebaugh, S.M.; and Linke, H.G.: Model Investigation of Inlet Plenum Flow Straightening Techniques for Altitude Test Facility. NASA TMX–3348, 1976.

TABLE I.—NOMINAL CAPABILITIES OF PROPULSION SYSTEMS LABORATORY

Maximum airflow from central equipment building, lb/sec	
At 55 psia	480
At 165 psia	400
At atmospheric conditions	750
Inlet temperature range, °F	
PSL3	–50 to 600
PSL4	–50 to 1200
Auxiliary air from other Lewis sources, lb/sec	
At 55 psia	65
At 140 psia	38
At 465 psia	76
Altitude range, ft	Sea level to 80 000

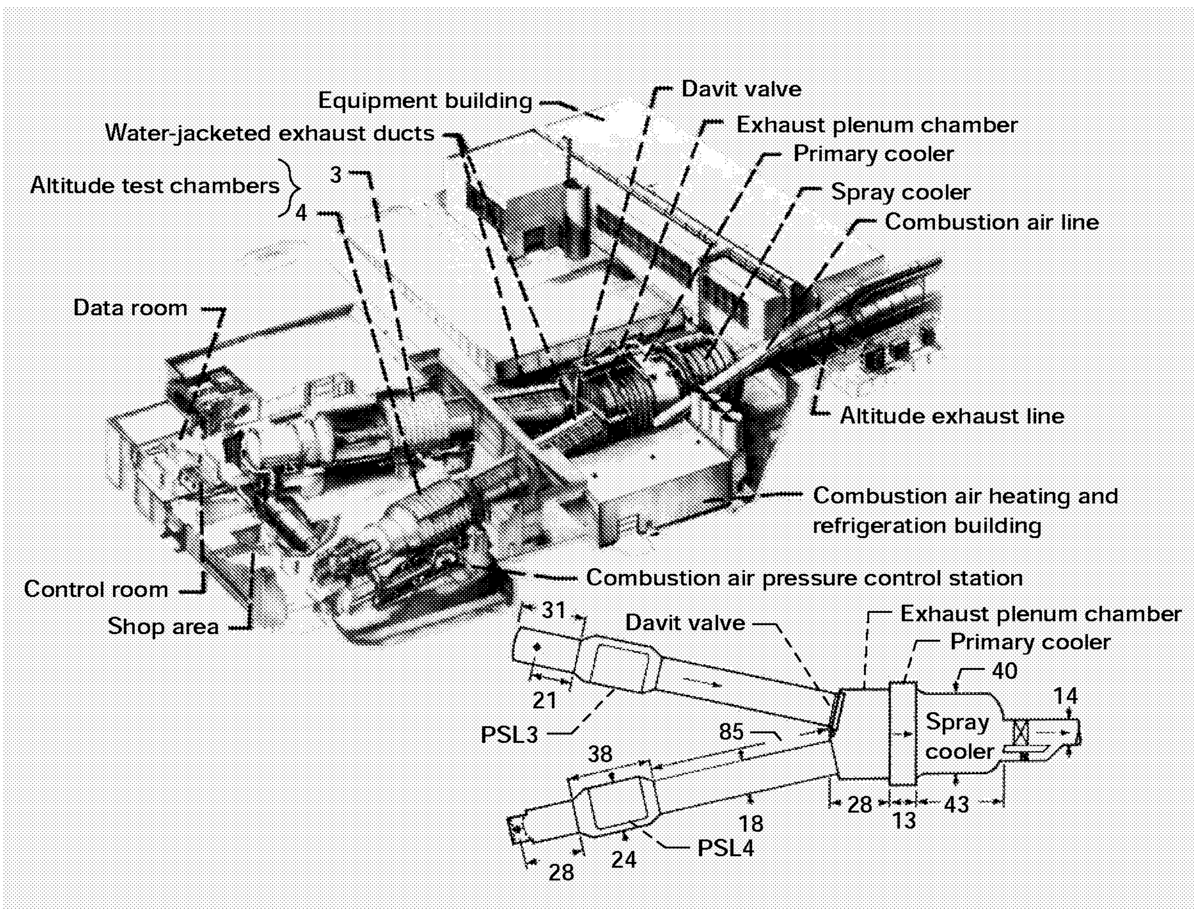


Figure 1.—Propulsion Systems Laboratory complex. All dimensions are in feet.

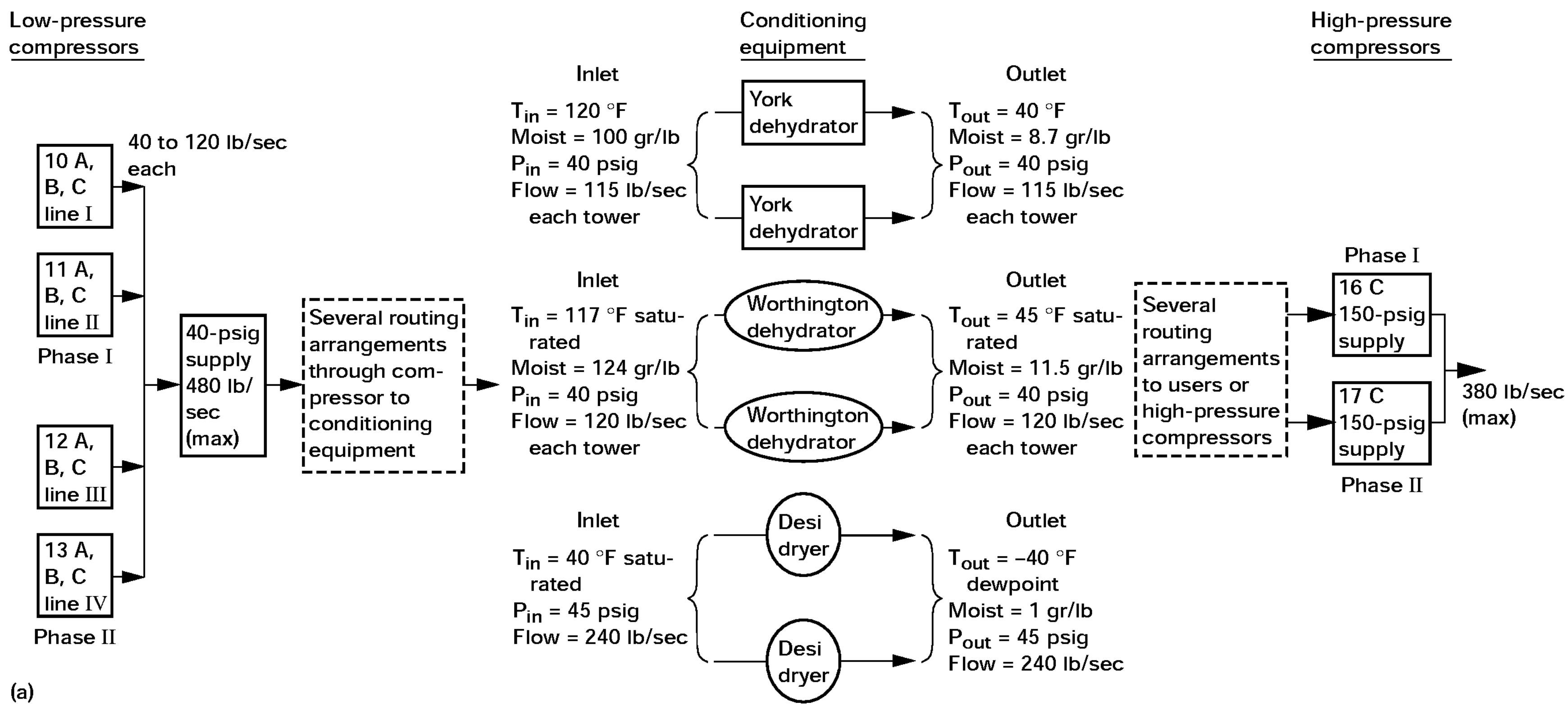


Figure 2.—Propulsion Systems Laboratory equipment building complex. (a) Combustion air supply and drying equipment. (b) Exhaust equipment.

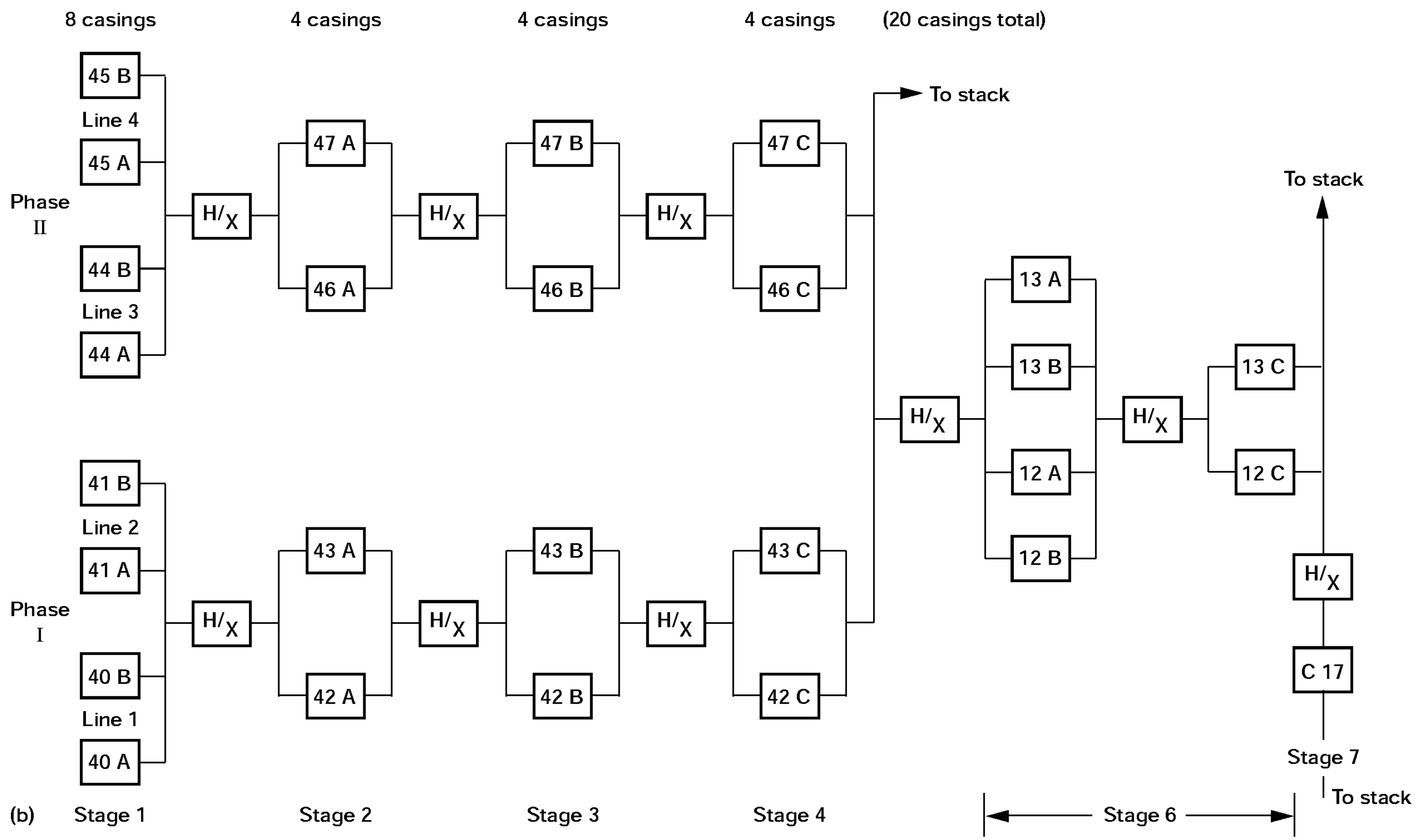


Figure 2.—Concluded. (b) Exhaust equipment. H/X refers to heat exchanger element.

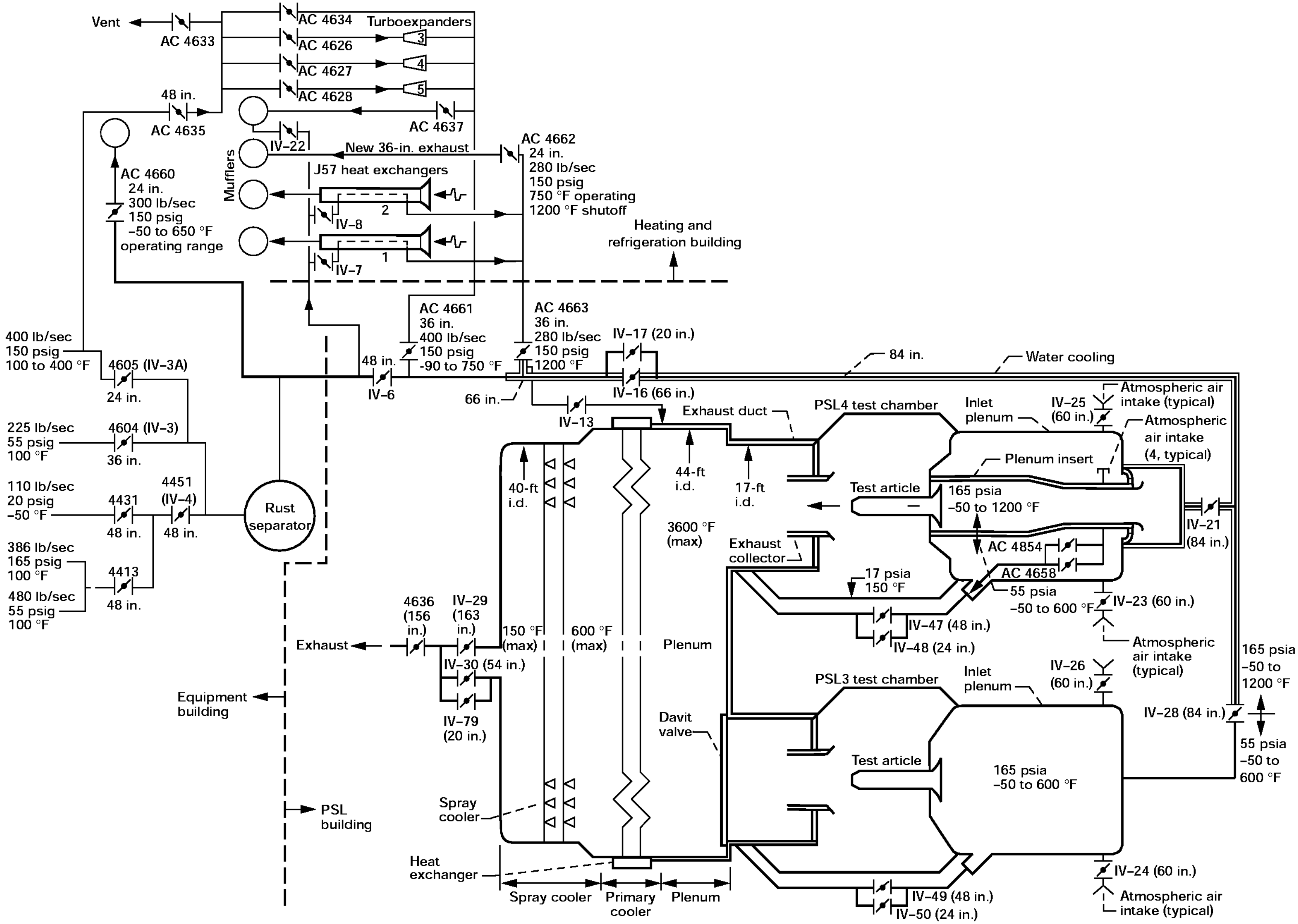


Figure 3.—Propulsion Systems Laboratory piping and valving, showing tie-in to equipment and heating and refrigeration buildings.

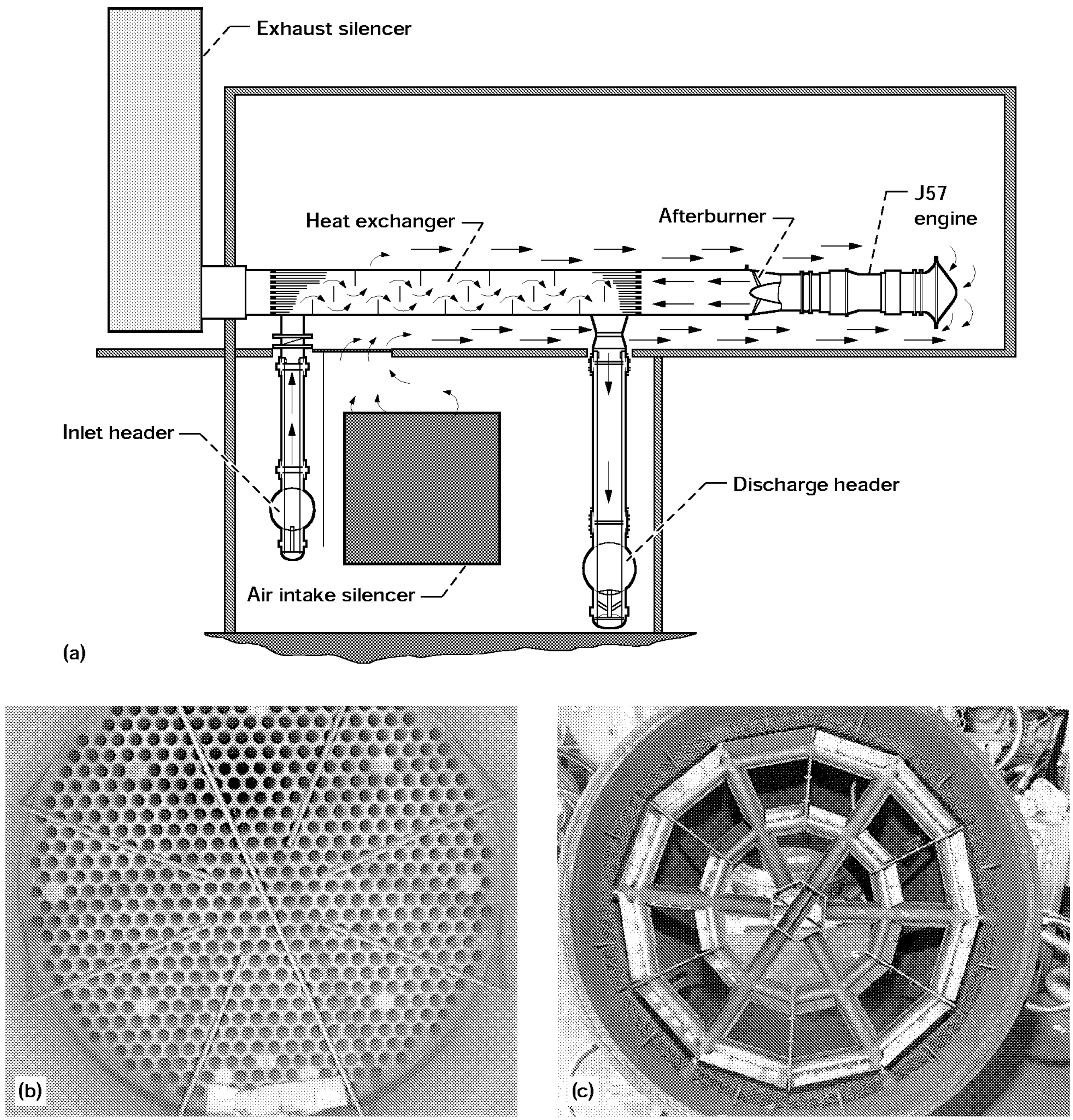


Figure 4.—Propulsion Systems Laboratory heat exchanger system. (a) Combustion air heaters. (b) Counterflow shell and tube heat exchanger. (c) Afterburner.

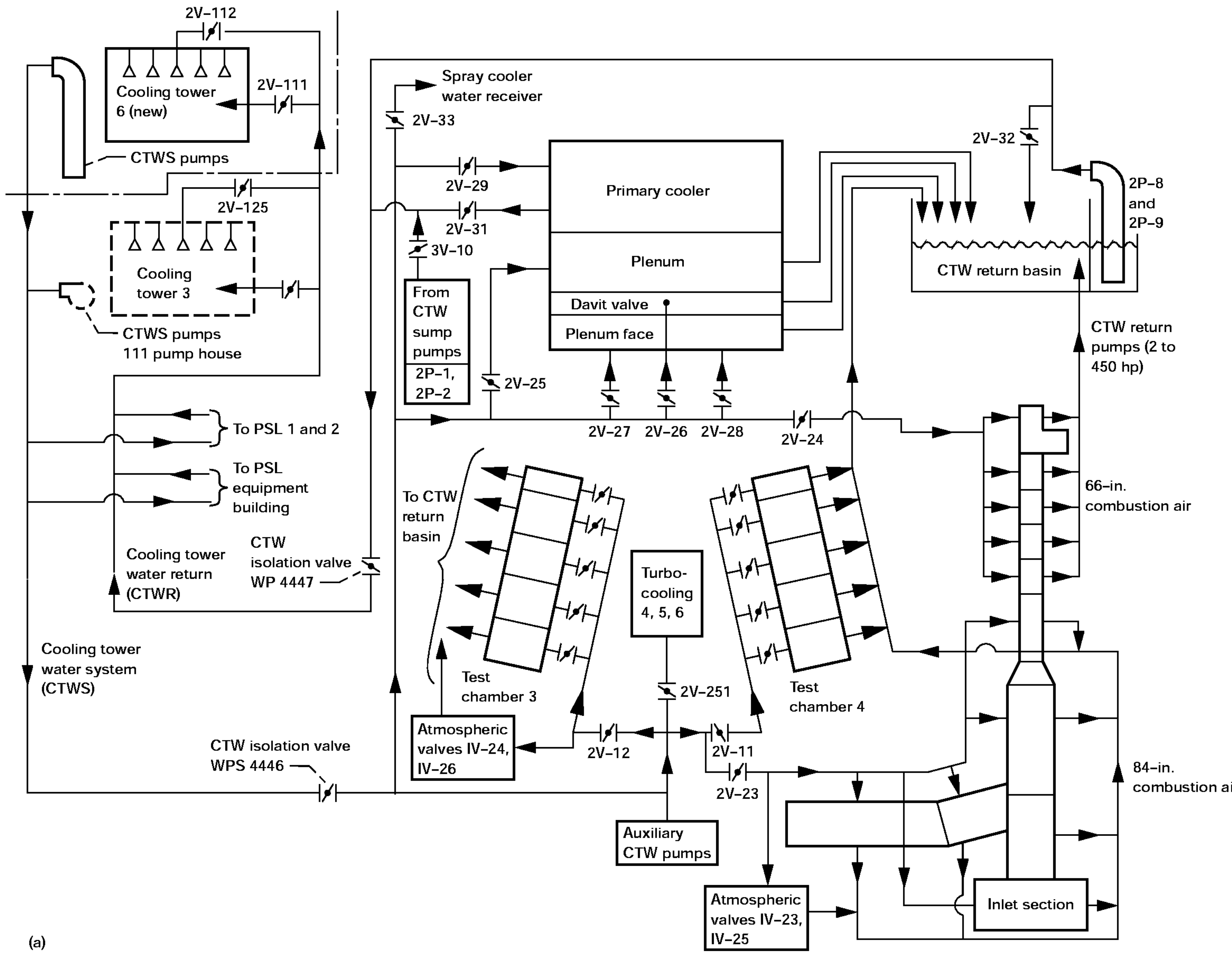


Figure 5.—Propulsion Systems Laboratory water systems. (a) Cooling tower; flow, 100 000 gal/min; pump discharge, 40 psig maximum; water temperature, 170 °F. (b) Spray cooler.

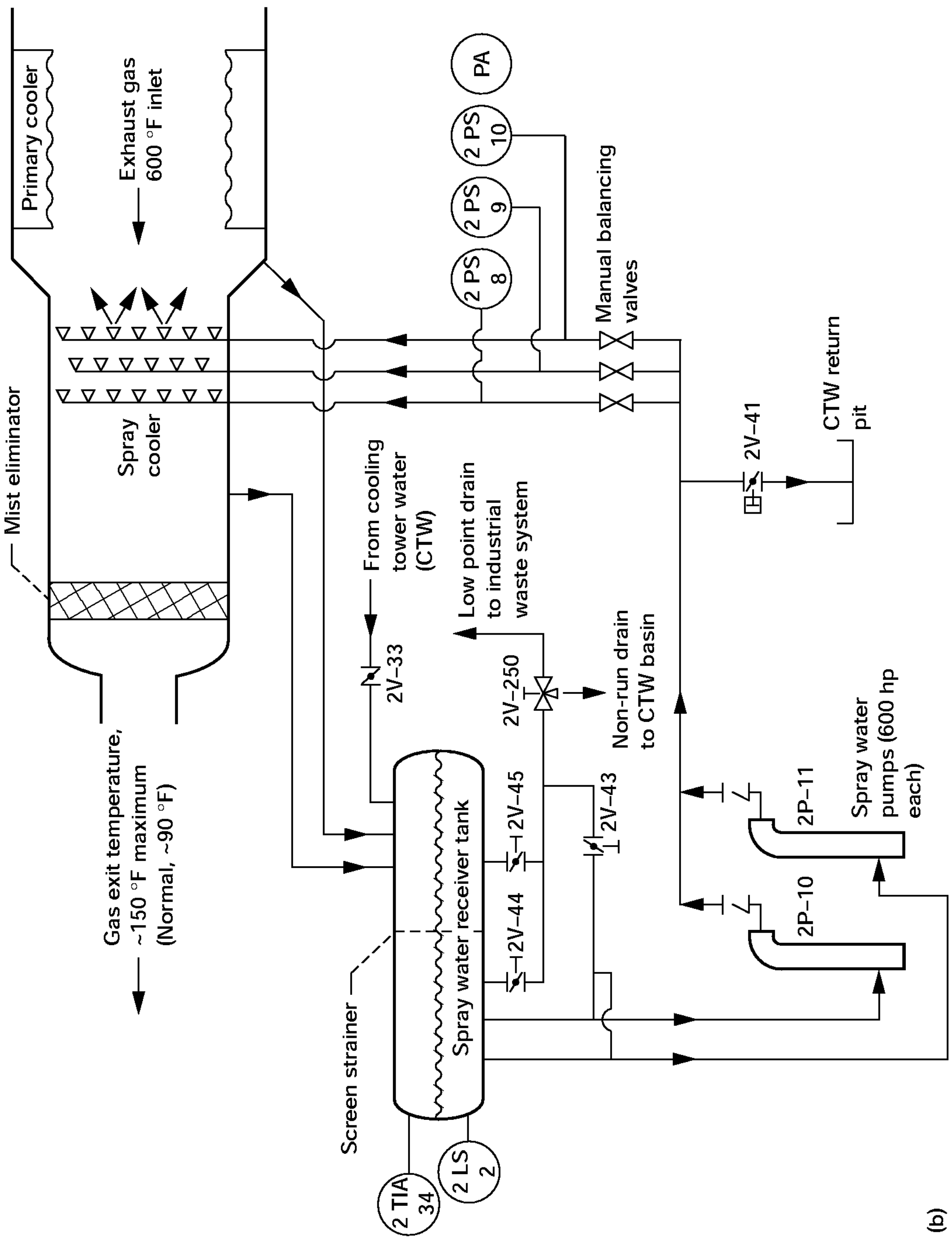
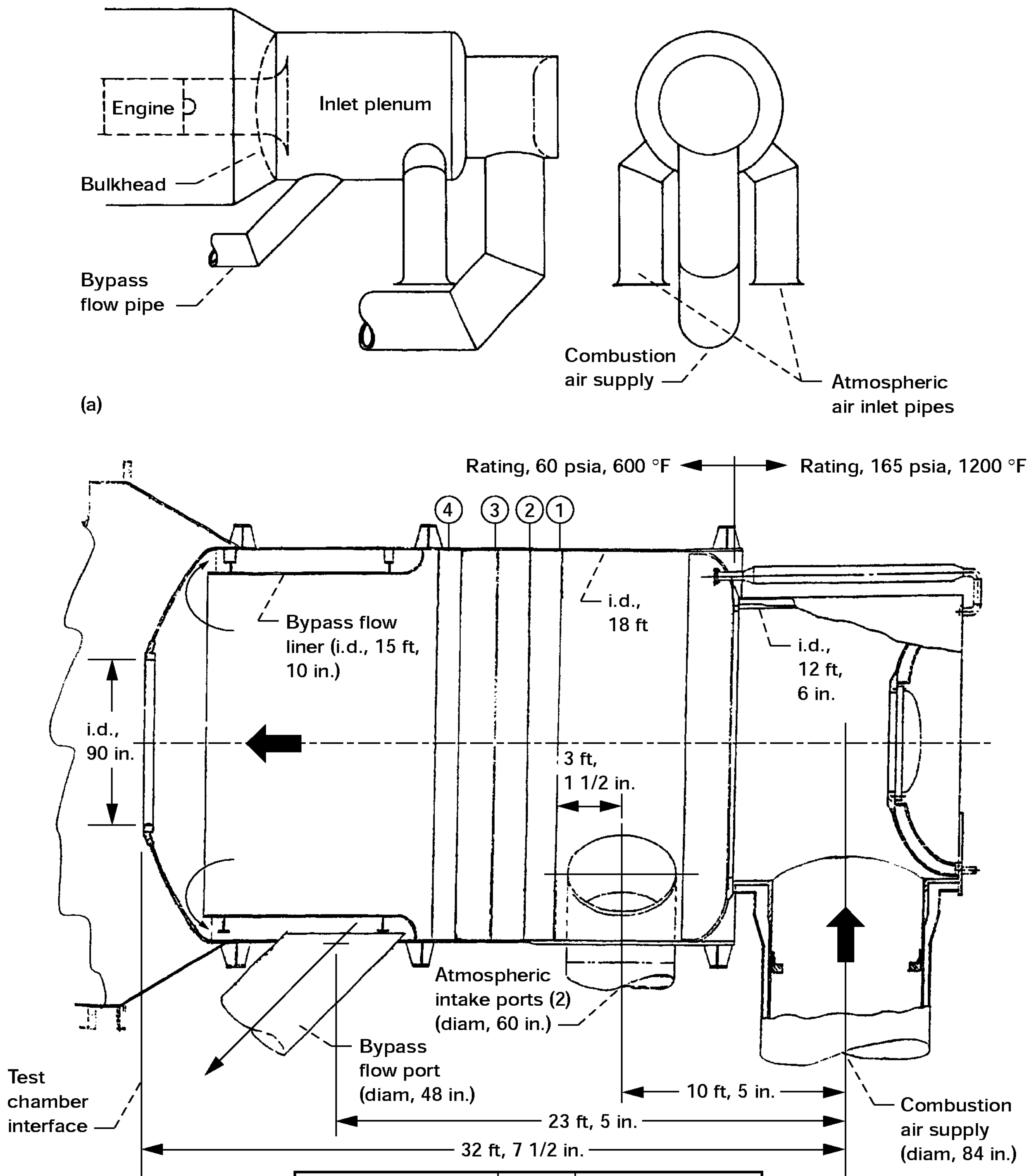


Figure 5.—Conclusion. (b) Spray cooler.



Screen[a]	Mesh	Wire diameter, in.
1	7	0.072
2	5	.080
3	6	.063
4 (straightener)[b]	--	----

[a]All flow conditioners spaced 1 ft, 6 in. apart.
[b]3 by 3 by 12 in. deep; 14-gauge wire.

(b)

Figure 6.—Configuration of original PSL4 inlet plenum. (a) Schematic. (b) Cross section.

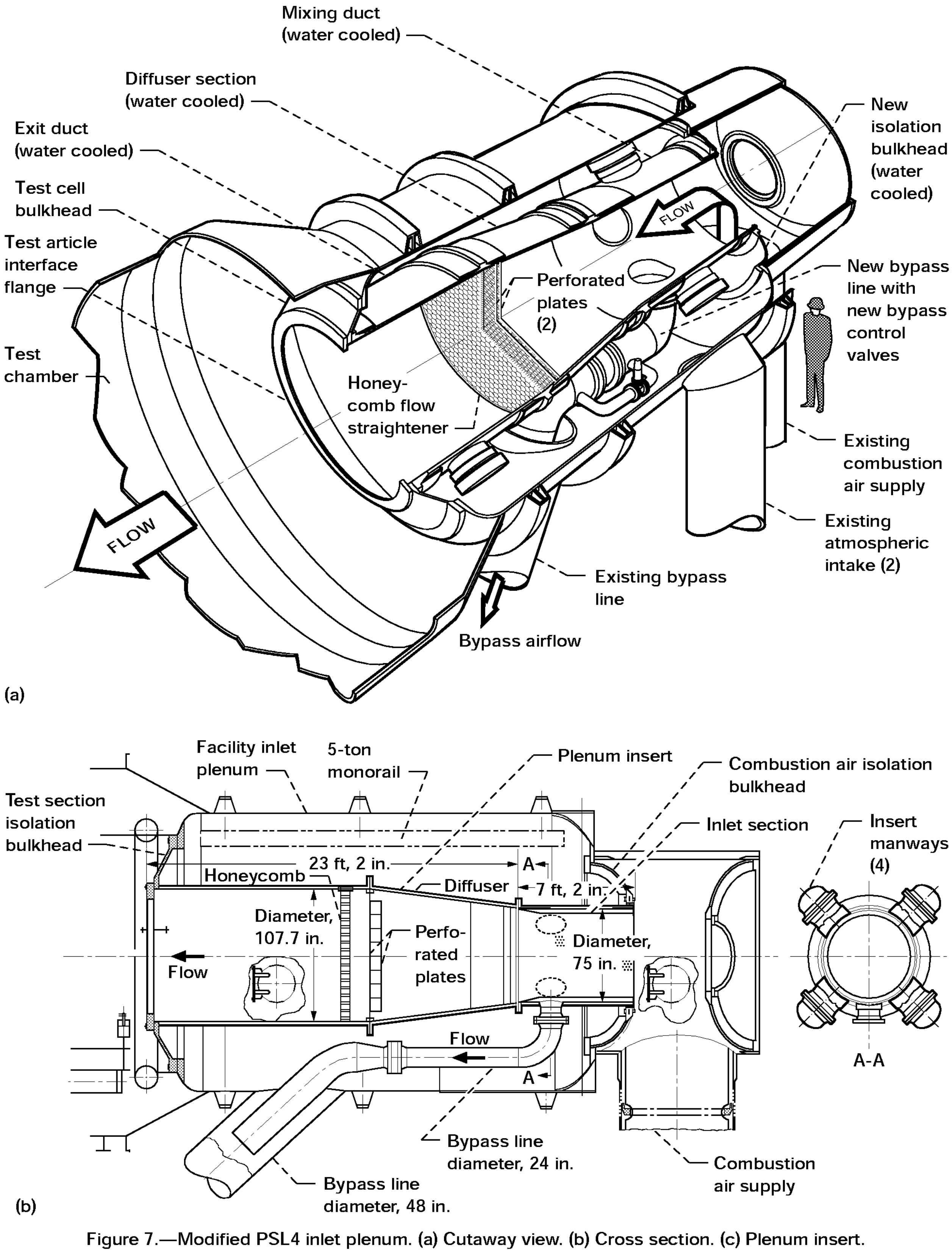


Figure 7.—Modified PSL4 inlet plenum. (a) Cutaway view. (b) Cross section. (c) Plenum insert.

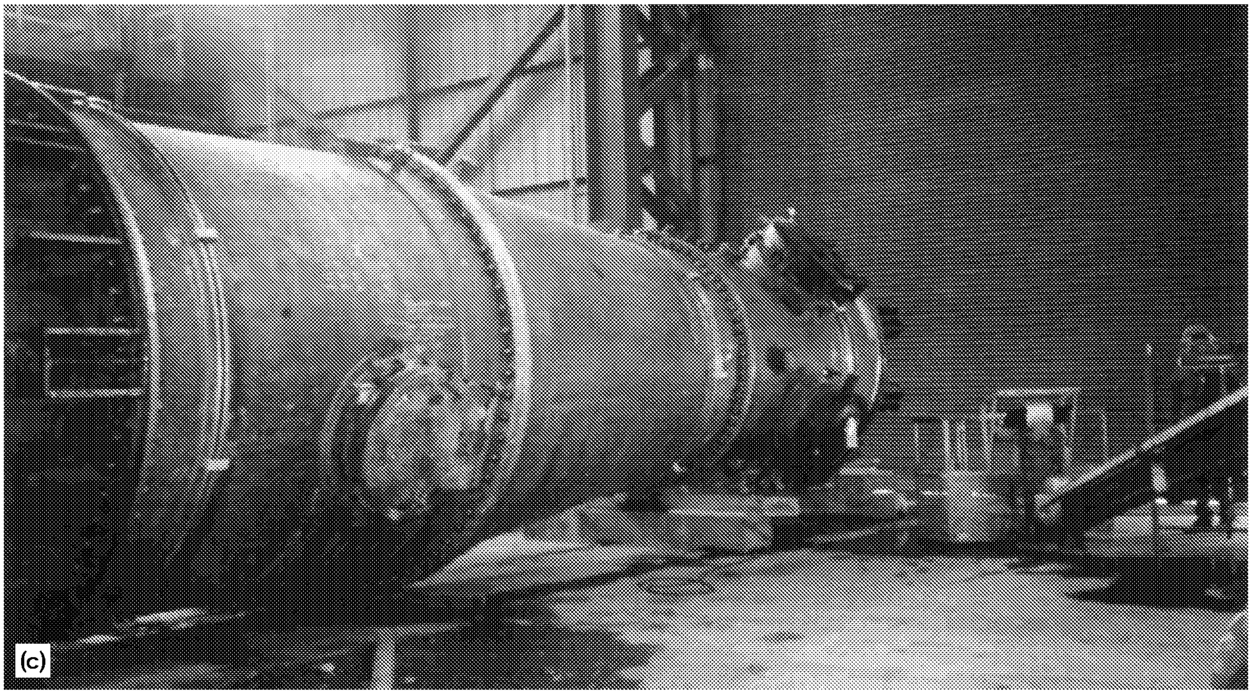


Figure 7.—Concluded. (c) Plenum insert.

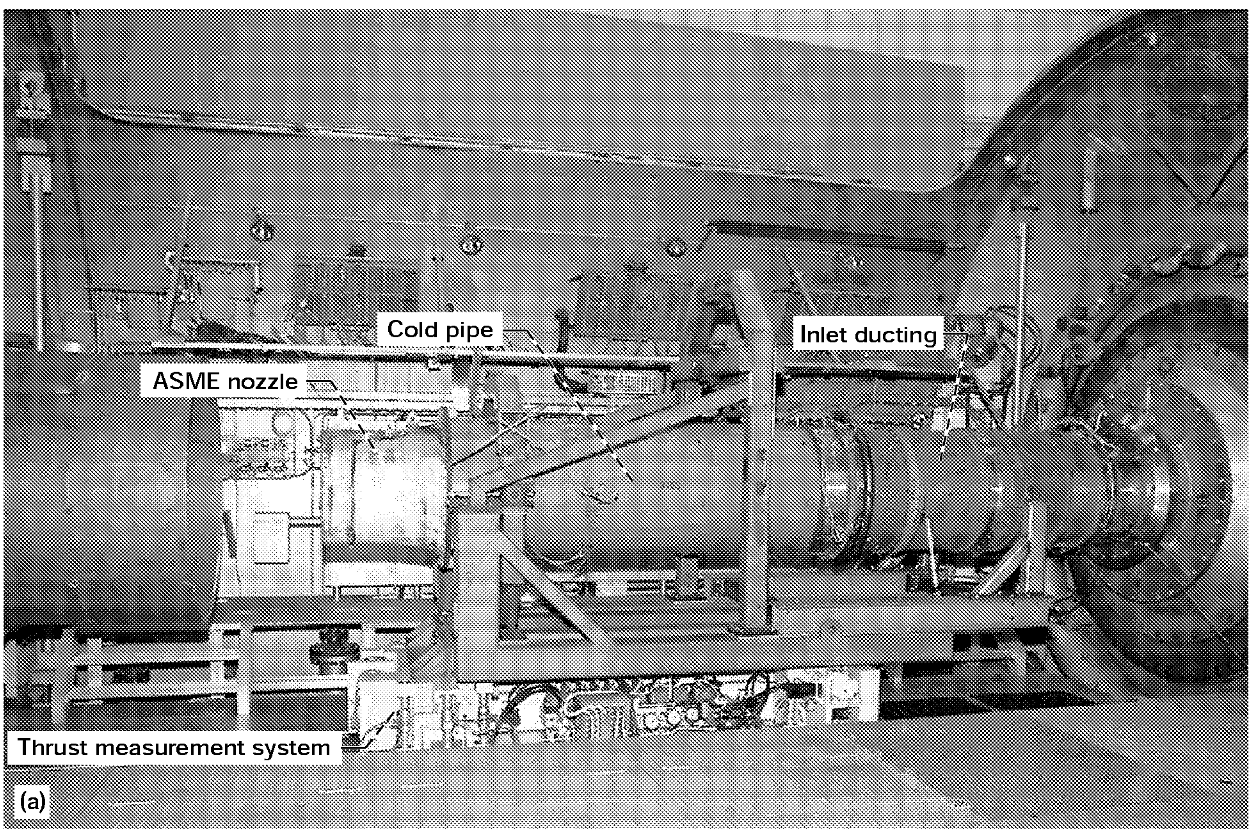
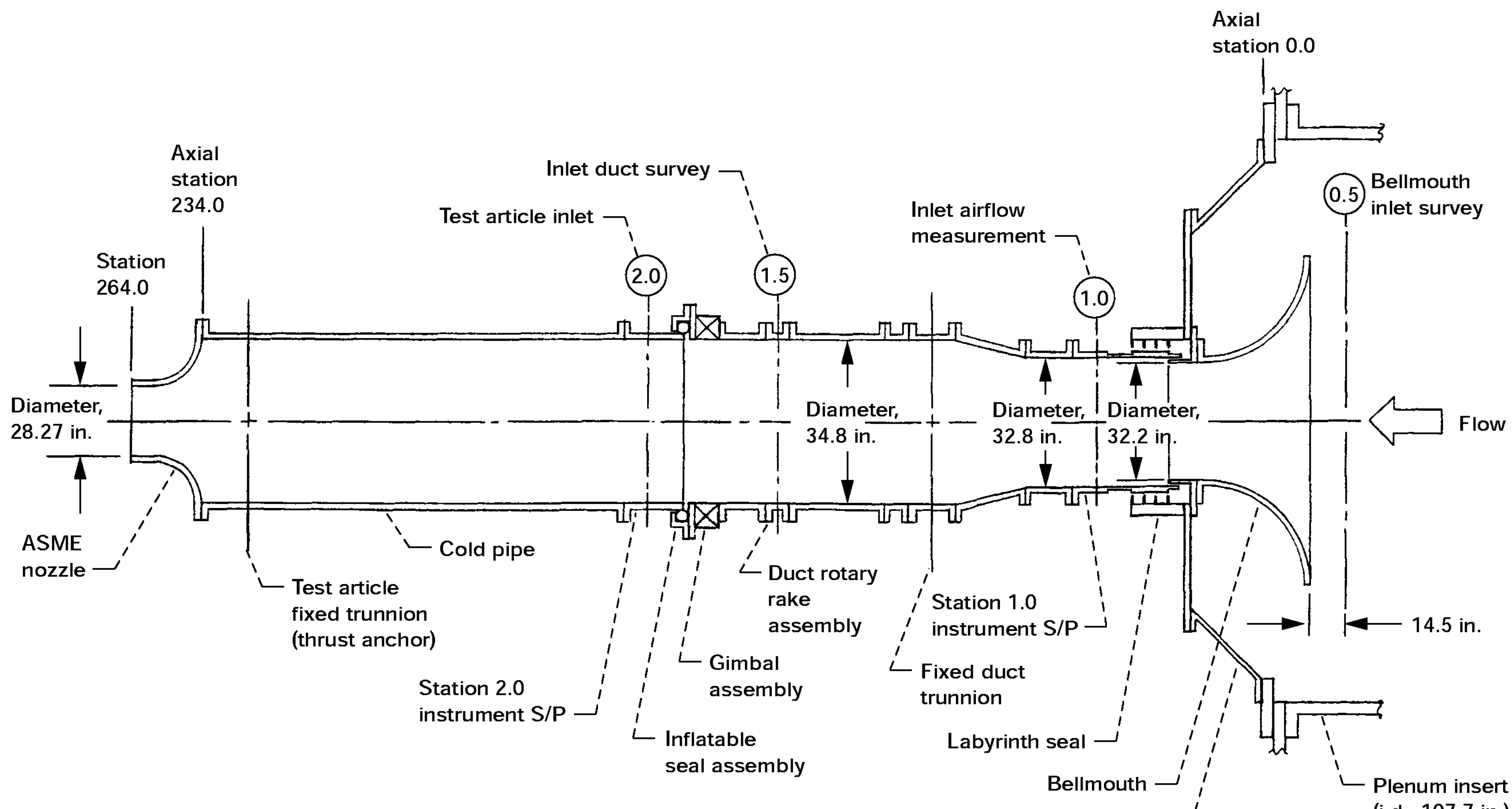
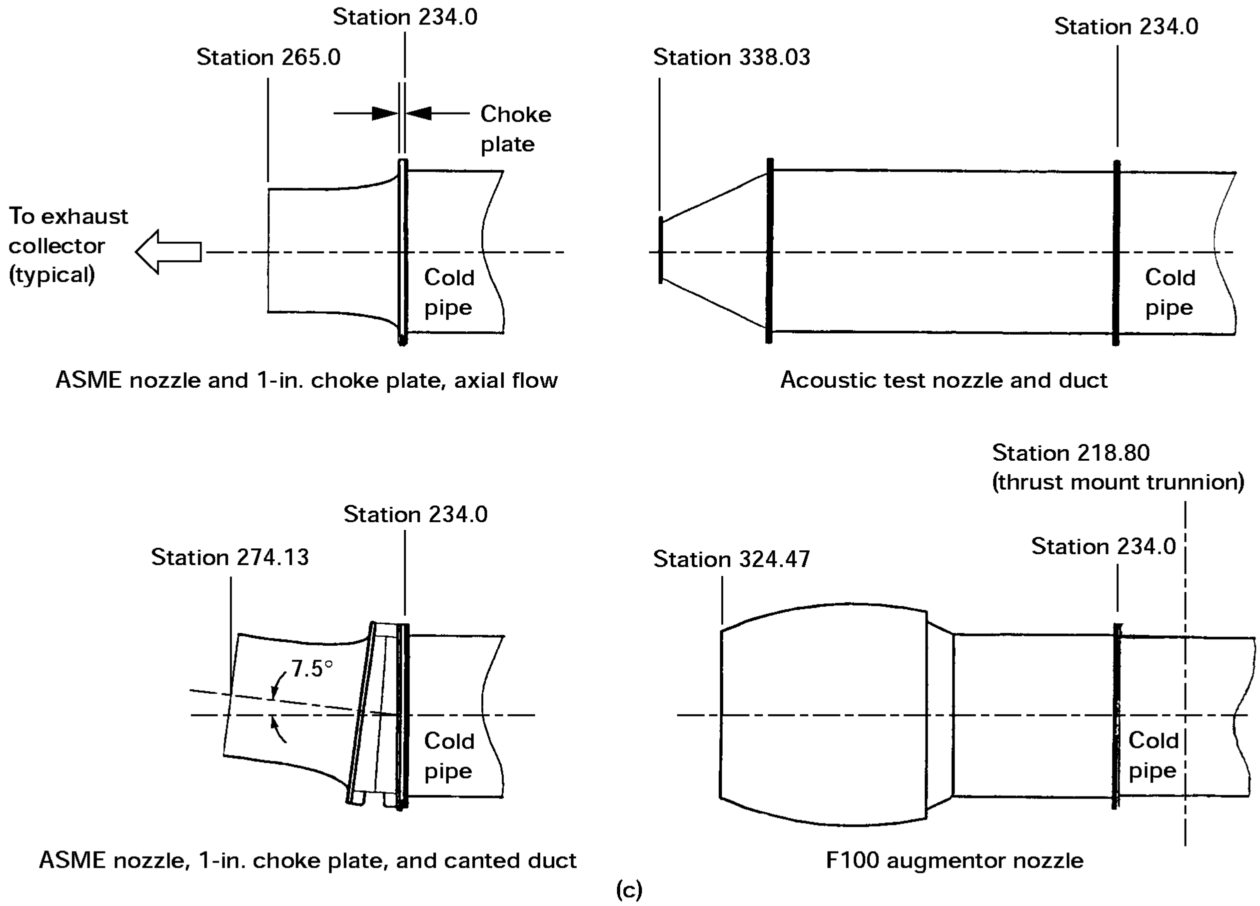


Figure 8.—Cold-pipe system. (a) Installation in PSL4. (b) Schematic. (c) Nozzle configurations. (d) F119 calibration nozzle installation in PSL4.



(b)

Figure 8.—Continued.— (b) Schematic.



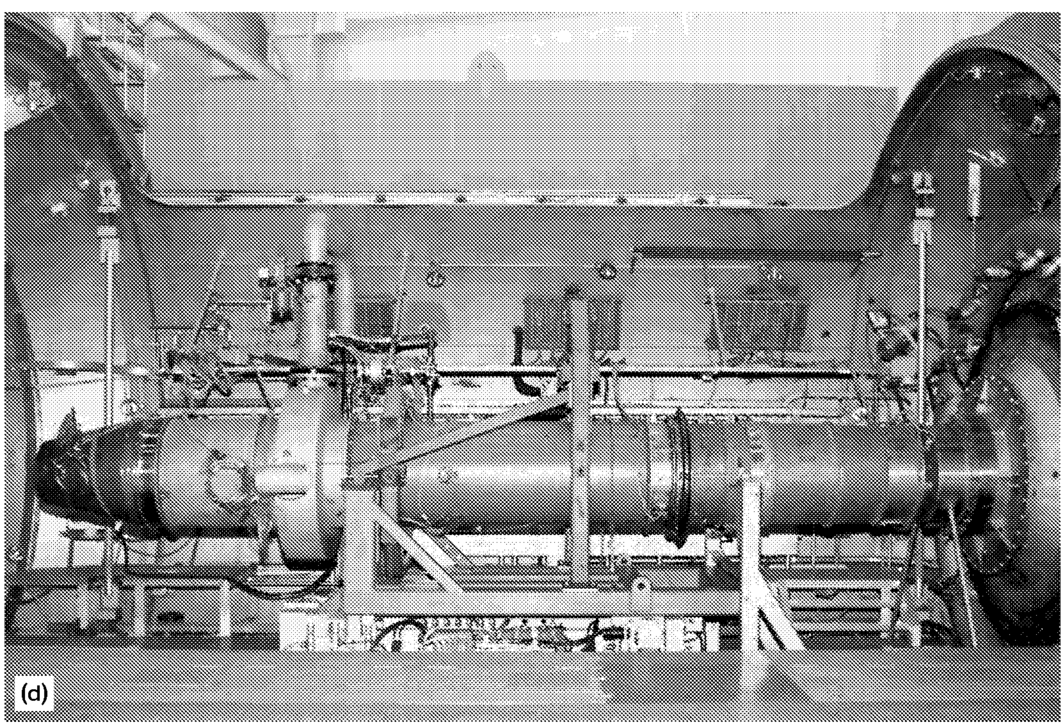
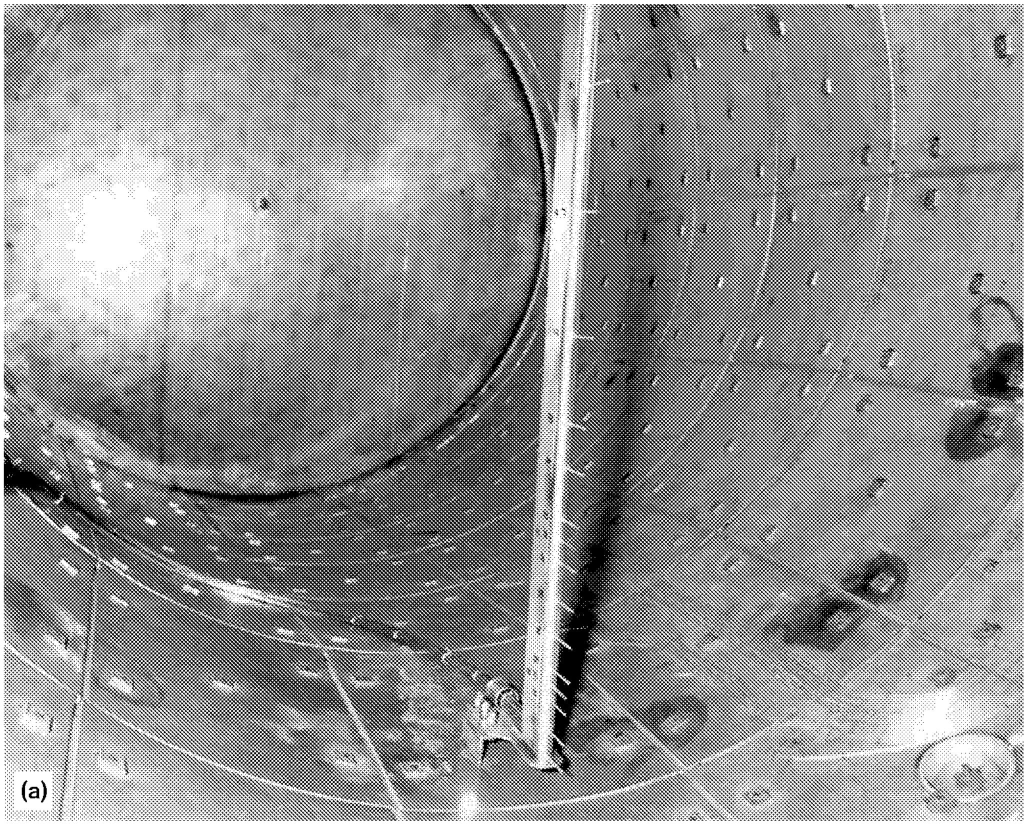


Figure 8.—Concluded. (c) Nozzle configurations. (d) F119 calibration nozzle installation in PSL4.



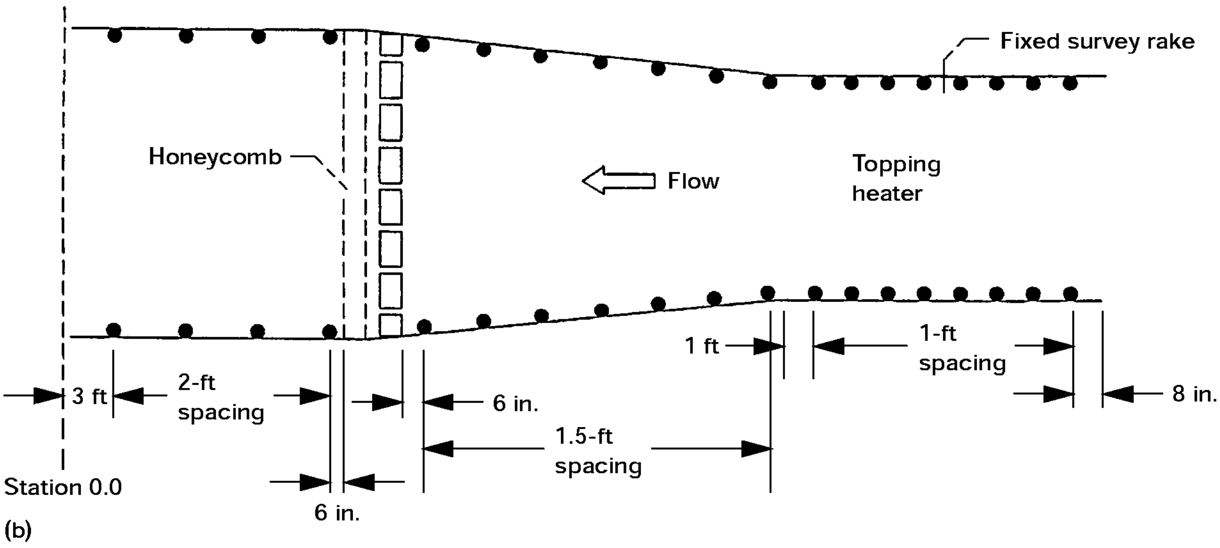
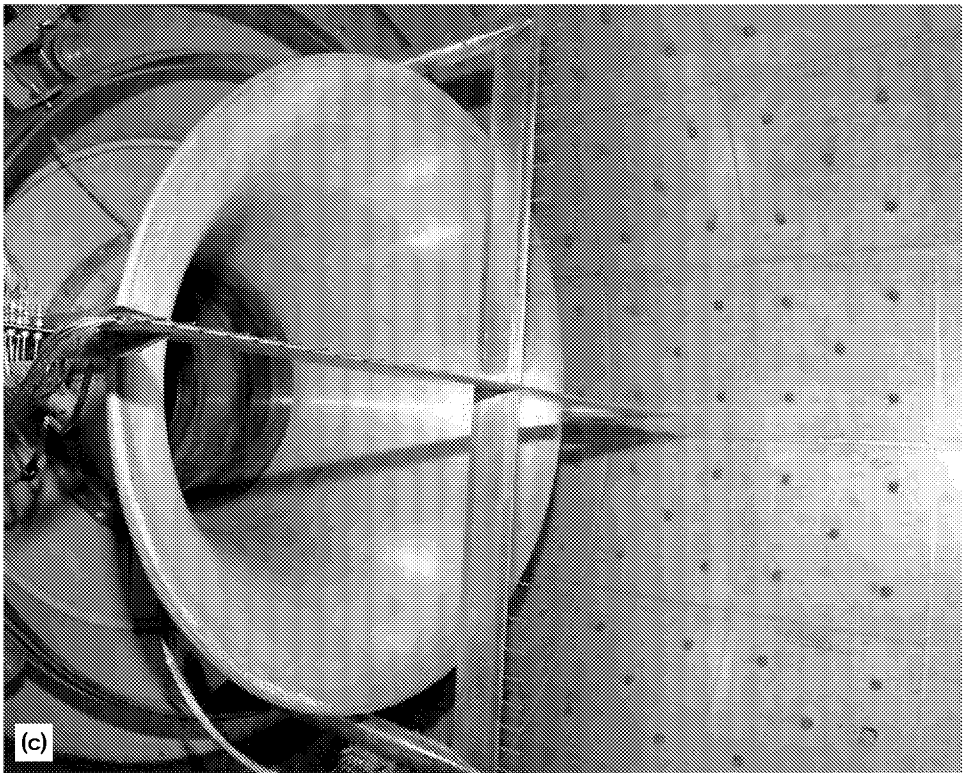


Figure 9.—Instrumentation installed in plenum insert. (a) Fixed survey rake in insert mixing duct (looking downstream toward perforated-plate flow straightener. (b) Static pressure taps. (c) Rotary survey rake in front of bellmouth. (d) Cold-pipe inlet duct rotary survey rake.



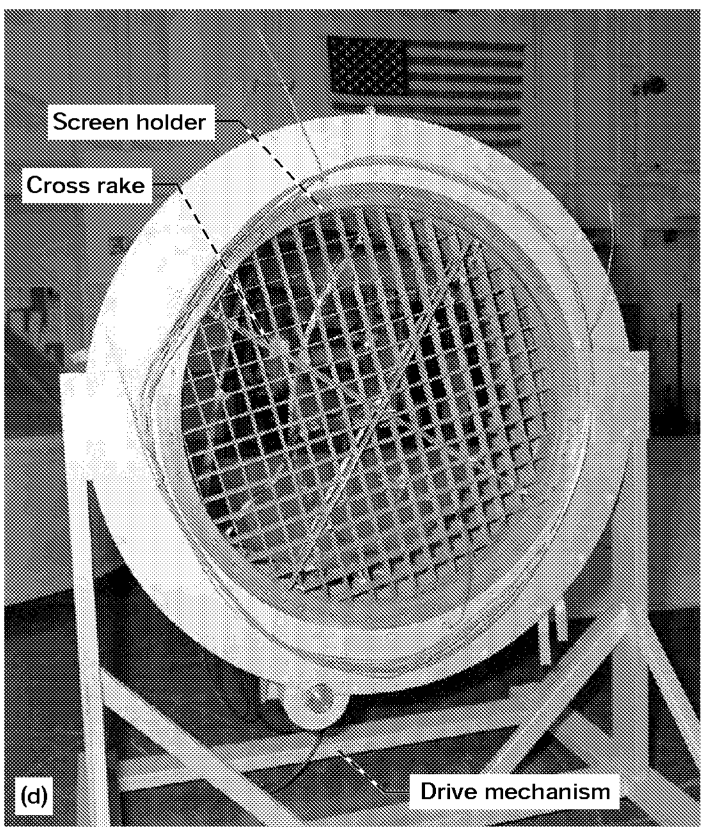
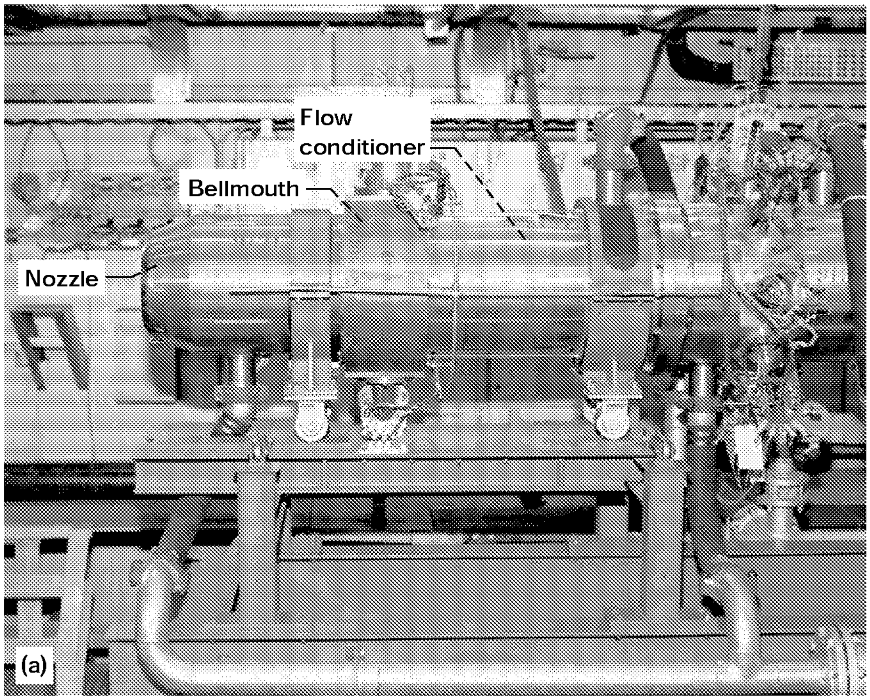


Figure 9.—Concluded.—(c) Rotary survey rake in front of bellmouth. (d) Rotary survey rake installed in cold-pipe inlet duct.



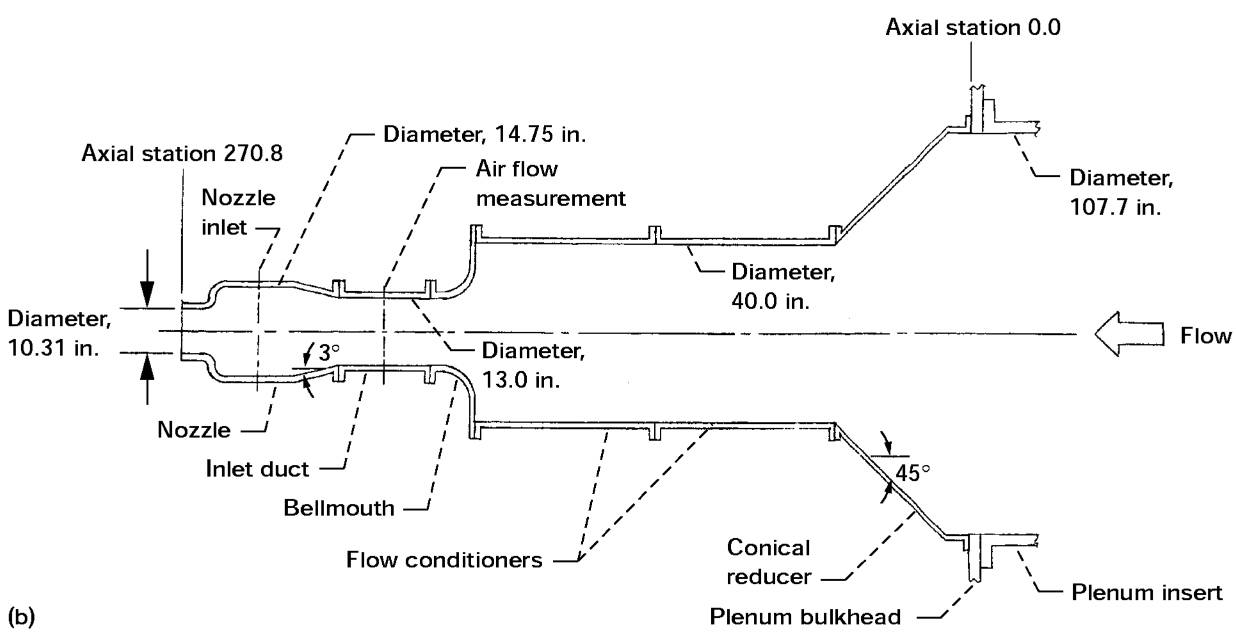


Figure 10.—Hot-pipe installation in PSL4. (a) Components. (b) Cross section.

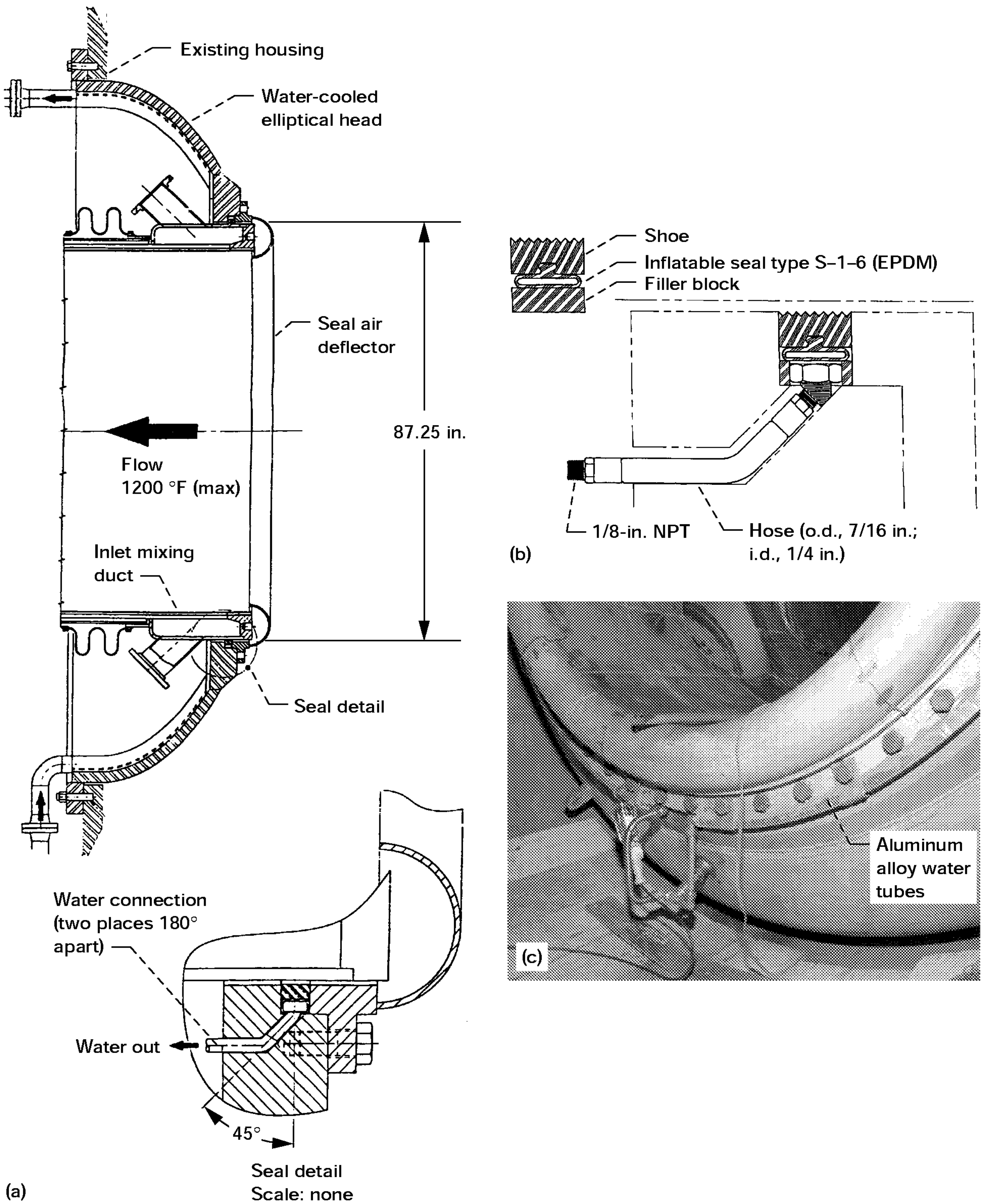


Figure 11.—Plenum insert inlet showing location and details of seal between insert and isolation bulkhead. (a) Original inflatable seal installation. (b) Final seal configuration. (c) Cooling modification to seal.

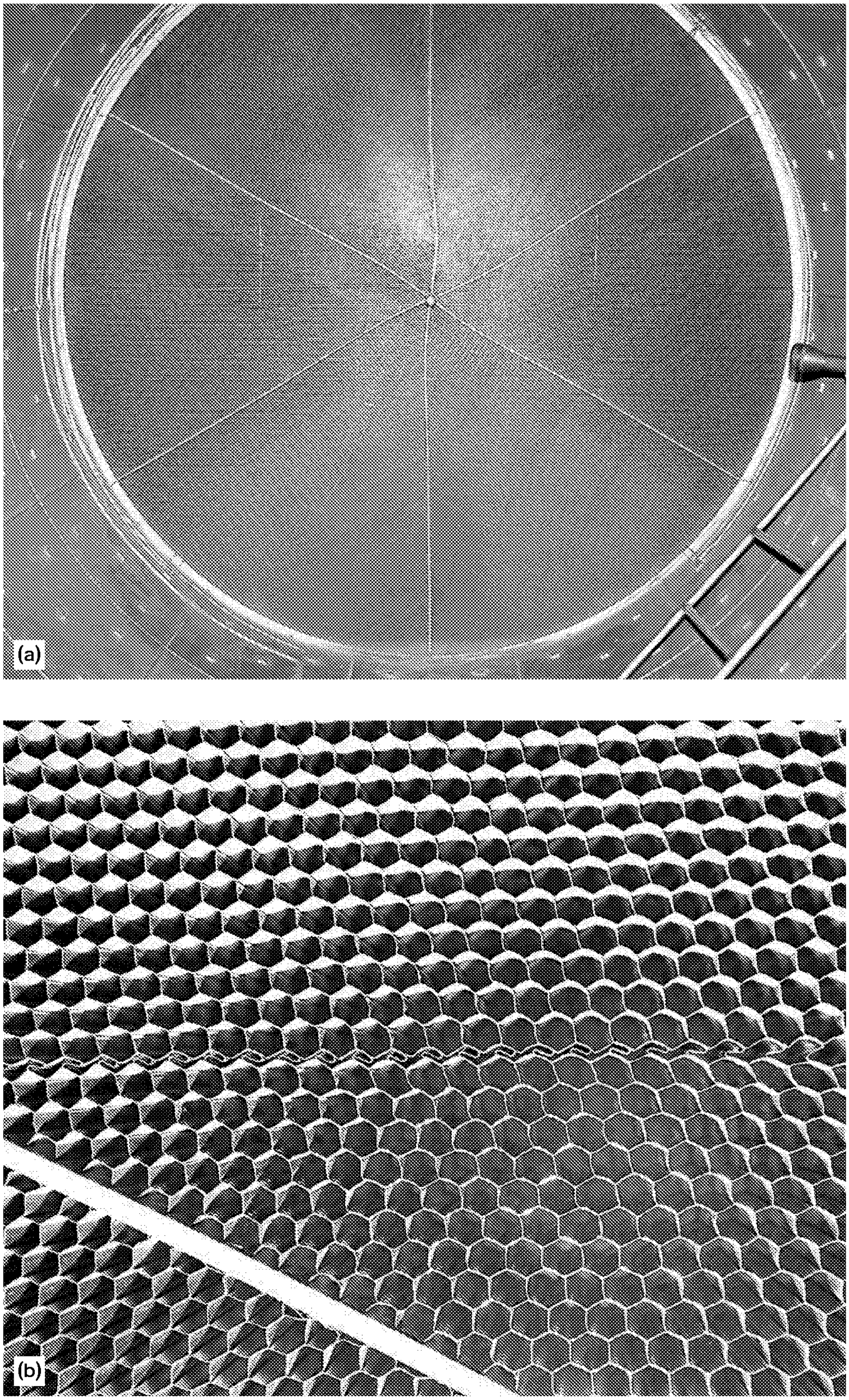


Figure 12.—Honeycomb flow straightener. (a) Aft looking forward to buckled support ribs and honeycomb panels. (b) Closeup of buckled honeycomb panel.

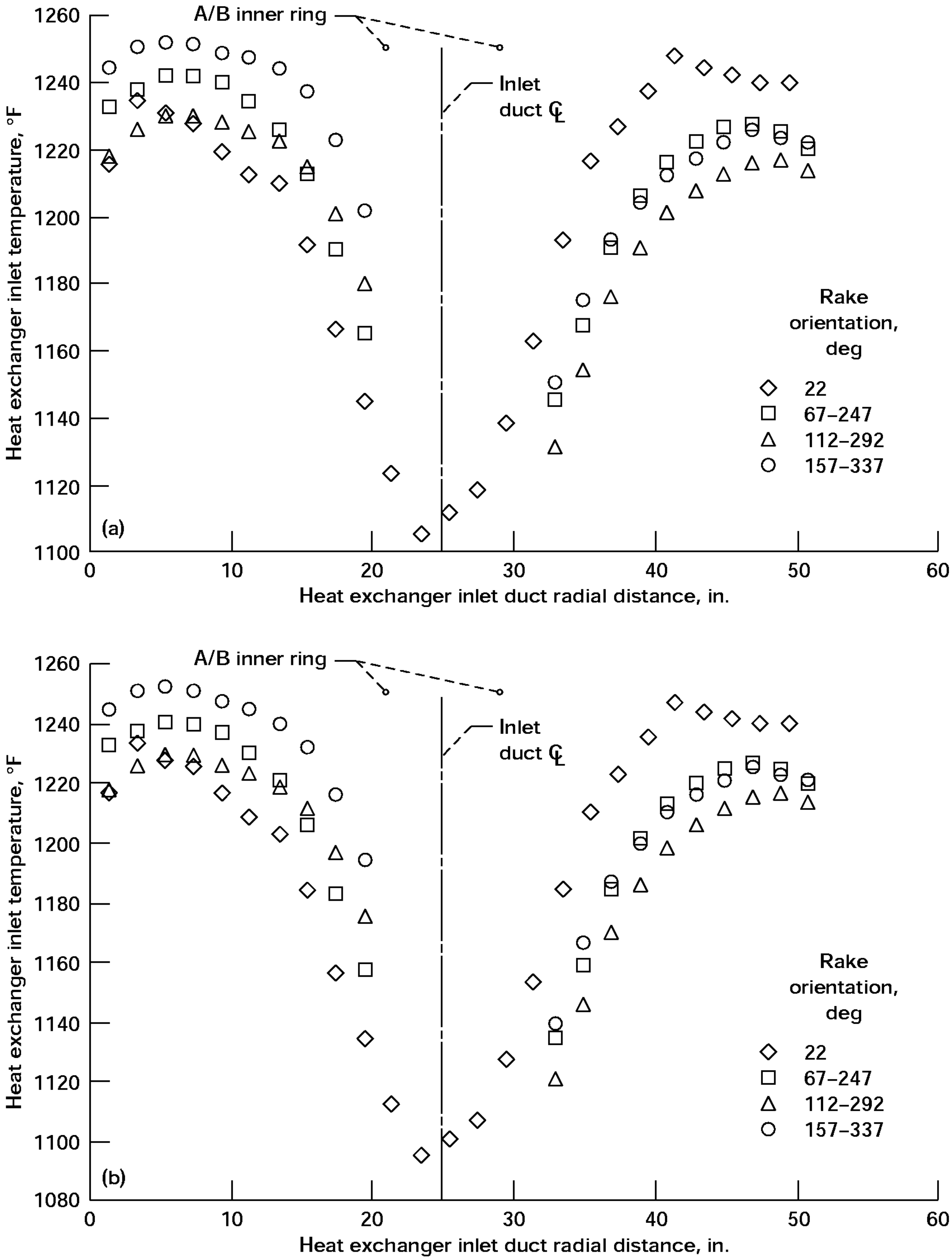


Figure 13.—Heat exchanger inlet gas (J57 exhaust) total temperature profiles. (a) Shellside air inlet: temperature, 111 °F and pressure, 79 psia; shellside air discharge temperature, 1075 °F; tubeside gas inlet temperature: maximum, 1252 °F and minimum, 1106 °F; tubeside gas pressure, 26 psia; PSL4 insert exit: maximum temperature, 868 °F, exit pressure, 64 psia, and airflow, 78.9 lb/sec. (b) Shellside air inlet: temperature, 116 °F and pressure, 140 psia; shellside air exit temperature, 945 °F; tubeside gas inlet temperature: maximum, 1252 °F and minimum, 1095 °F; tubeside gas pressure, 26 psia; PSL4 insert exit: maximum temperature, 844 °F, exit pressure, 129 psia, and airflow, 159 lb/sec.

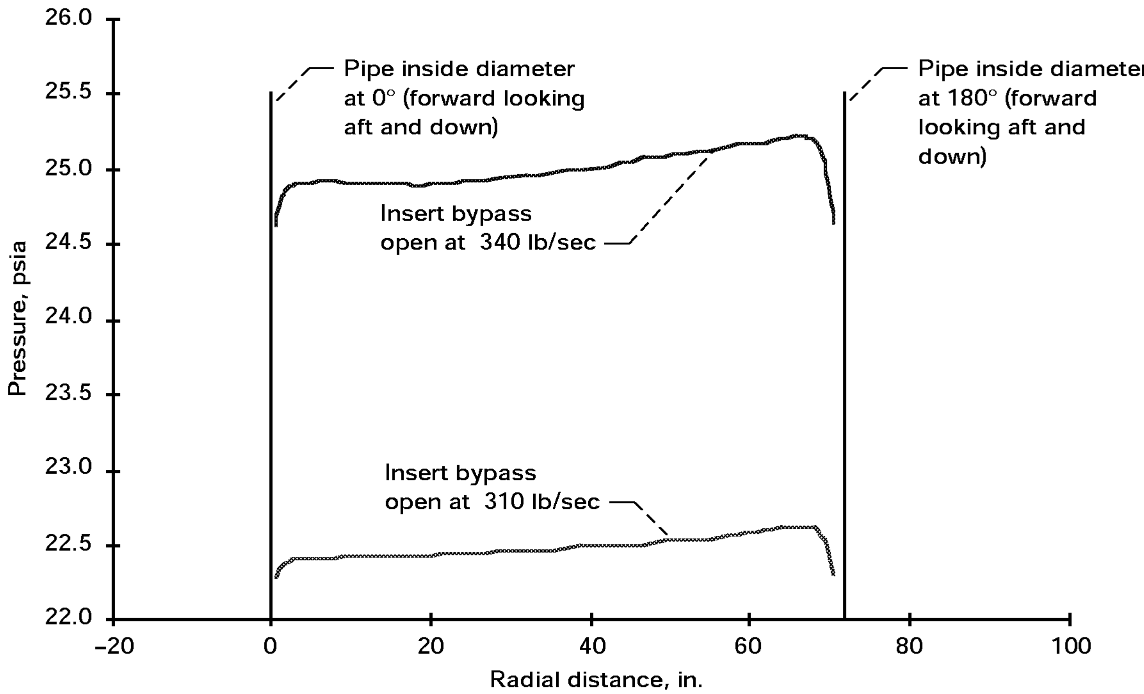


Figure 14.—Total pressure profiles at PSL4 plenum insert combustion air supply inlet (84-in. pipe shown in fig 6(b)).

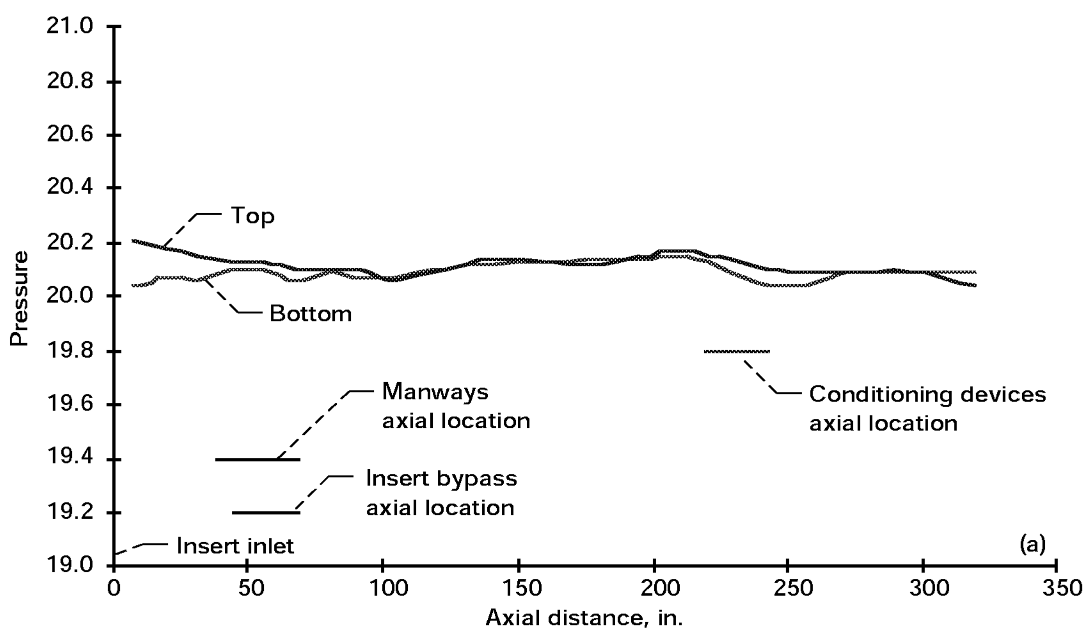
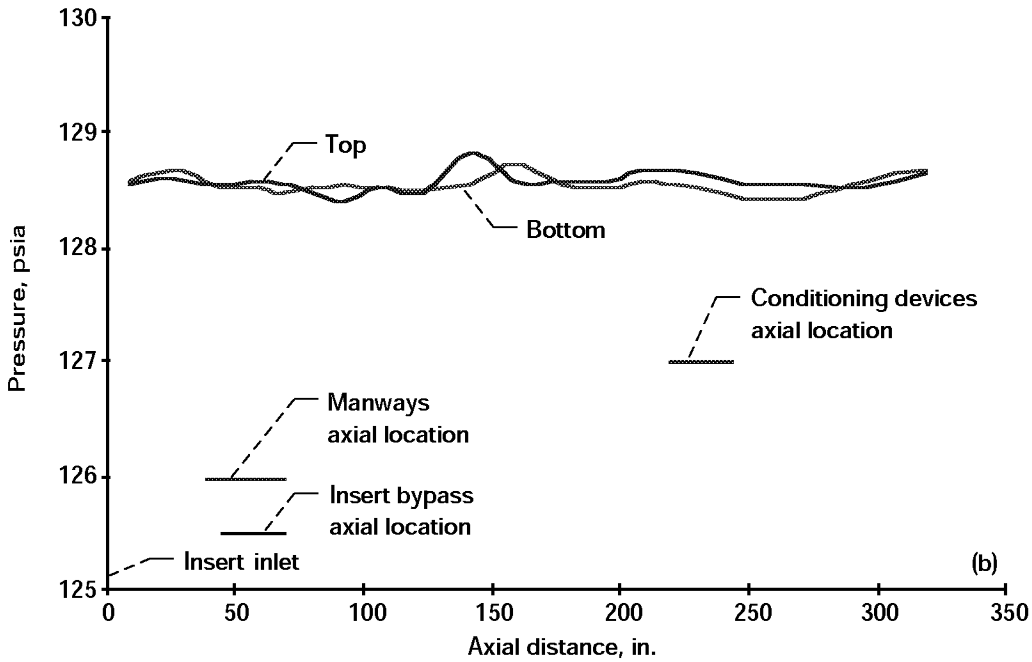


Figure 15.—Plenum insert axial wall static pressure distribution. (a) Facility configuration: plenum insert manways open, plenum bypass open, plenum atmospheric ports closed, plenum insert bypass closed, inlet temperature, ambient. (b) Facility configuration: plenum insert manways closed, plenum bypass open, plenum atmospheric ports open, plenum insert bypass closed; inlet temperature, 844 °F. (c) Facility configuration: plenum insert manways closed, plenum bypass open, plenum atmospheric ports closed, plenum insert bypass open; inlet temperature, ambient. (d) Facility configuration: plenum insert manways closed, plenum bypass open, plenum atmospheric ports closed, plenum insert bypass closed; inlet temperature, ambient.



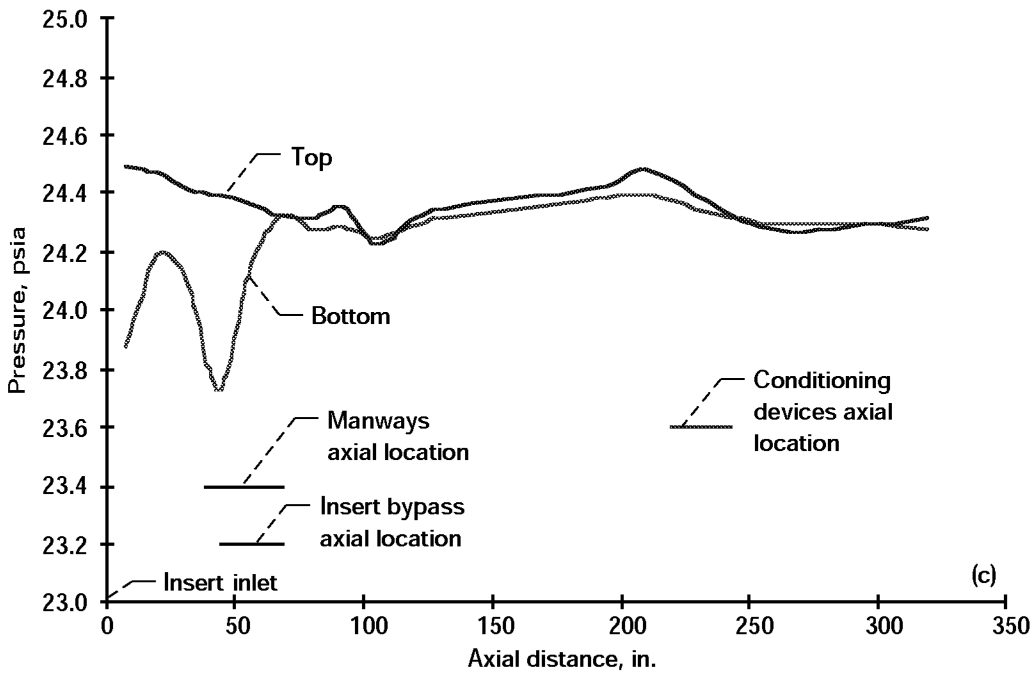


Figure 15.—Continued. (b) Facility configuration: plenum insert manways closed, plenum bypass open, plenum atmospheric ports open, plenum insert bypass closed; inlet temperature, 844 °F. (c) Facility configuration: plenum insert manways closed, plenum bypass open, plenum atmospheric ports closed, plenum insert bypass open; inlet temperature, ambient.

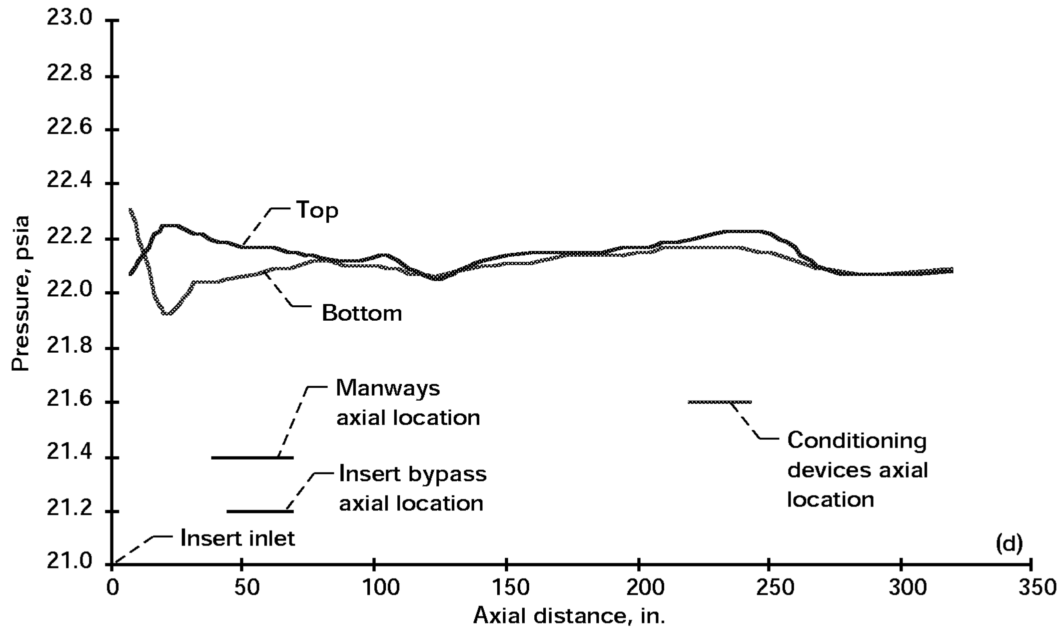


Figure 15.—Concluded. (d) Facility configuration: plenum insert manways closed, plenum bypass open, plenum atmospheric ports closed, plenum insert bypass closed; inlet temperature, ambient.

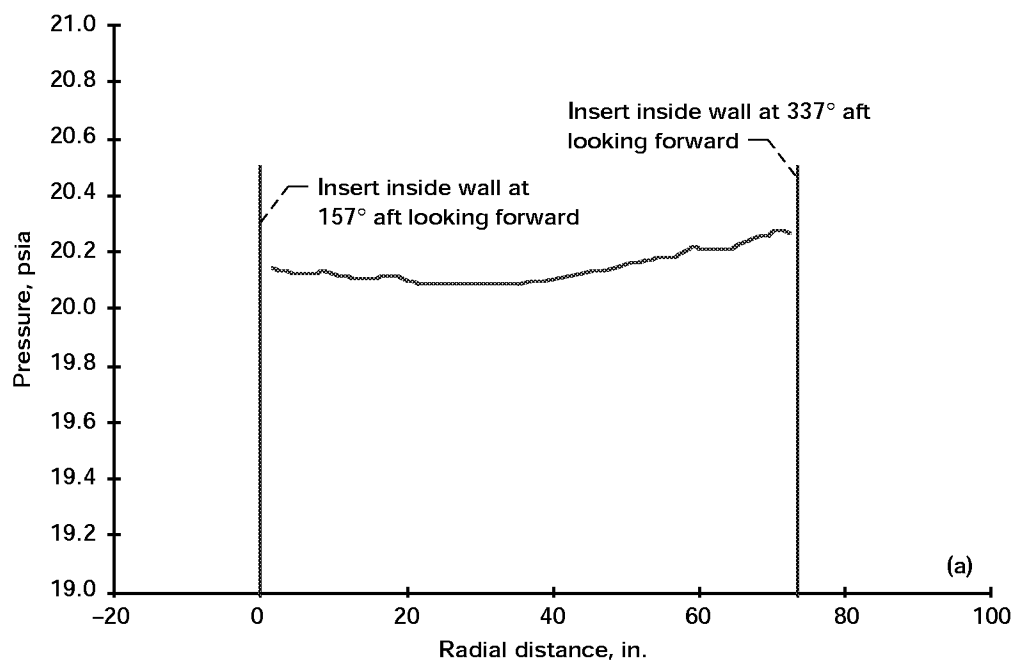
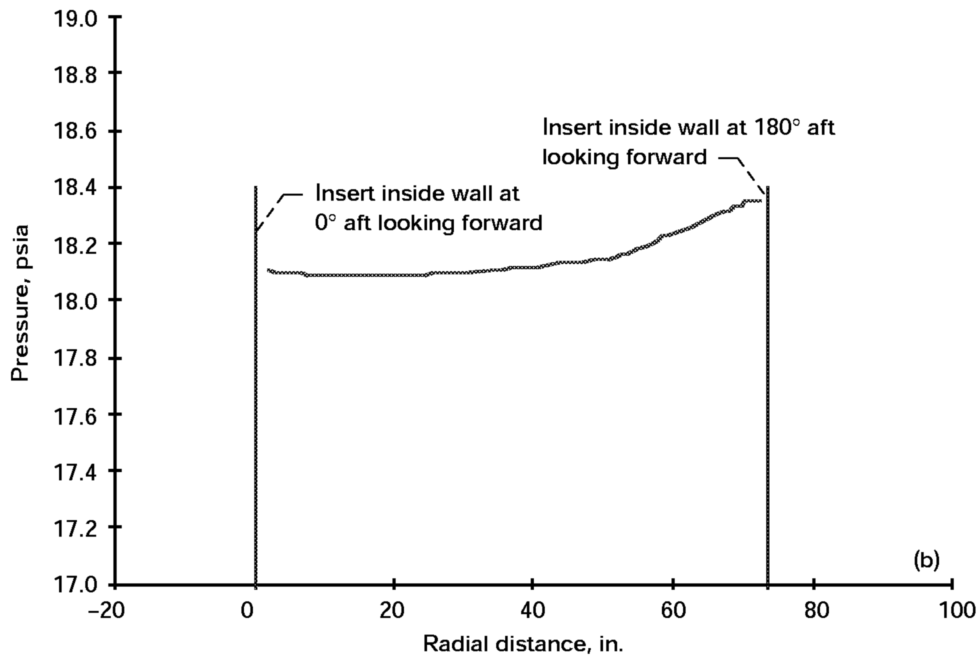


Figure 16.—Plenum insert total pressure distribution at plenum insert diffuser inlet. (a) Facility configuration: plenum insert manways open, plenum bypass open, plenum atmospheric ports closed, plenum insert bypass closed; inlet temperature, ambient. (b) Facility configuration: plenum insert manways closed, plenum bypass open, plenum atmospheric ports closed, plenum insert bypass closed; inlet temperature, ambient. (c) Facility configuration: plenum insert manways closed, plenum bypass open, plenum atmospheric ports closed, plenum insert bypass closed; inlet temperature, ambient. (d) Facility configuration: plenum insert manways closed, plenum bypass open, plenum atmospheric ports closed, plenum insert bypass open; inlet temperature, ambient.



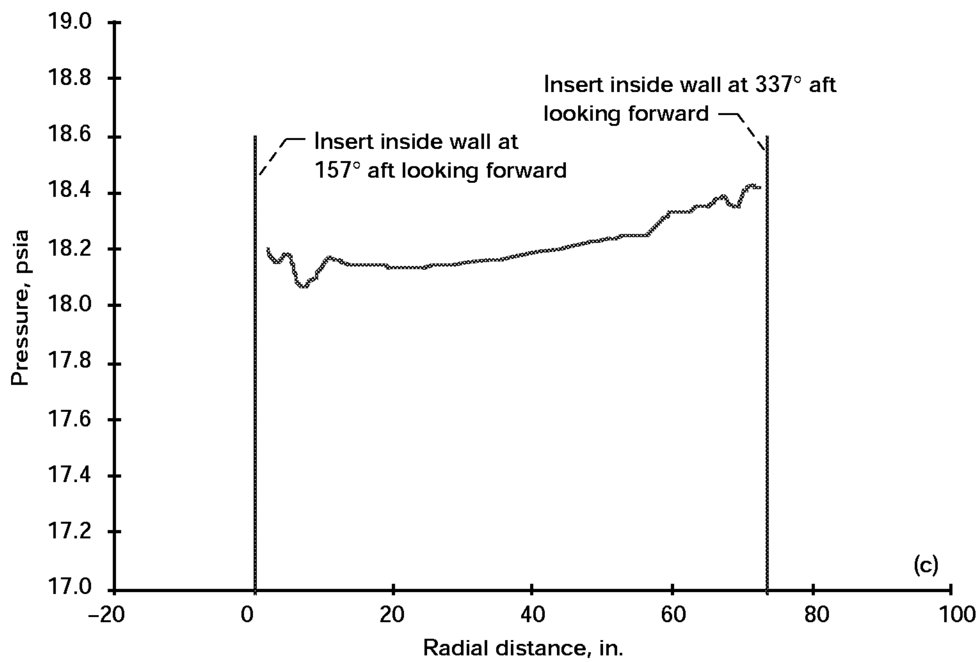


Figure 16.—Continued. (b) Facility configuration: plenum insert manways closed, plenum bypass open, plenum atmospheric ports closed, plenum insert bypass closed; inlet temperature, ambient. (c) Facility configuration: plenum insert manways closed, plenum bypass open, plenum atmospheric ports closed, plenum insert bypass closed; inlet temperature, ambient.

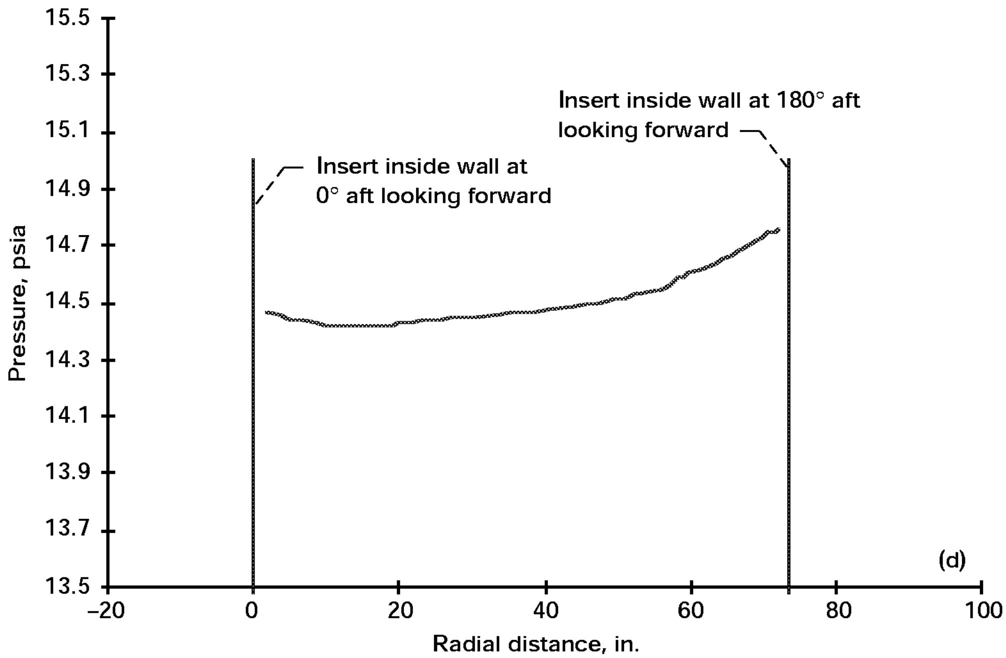


Figure 16.—Concluded. (d) Facility configuration: plenum insert manways closed, plenum bypass open, plenum atmospheric ports closed, plenum insert bypass open; inlet temperature, ambient.

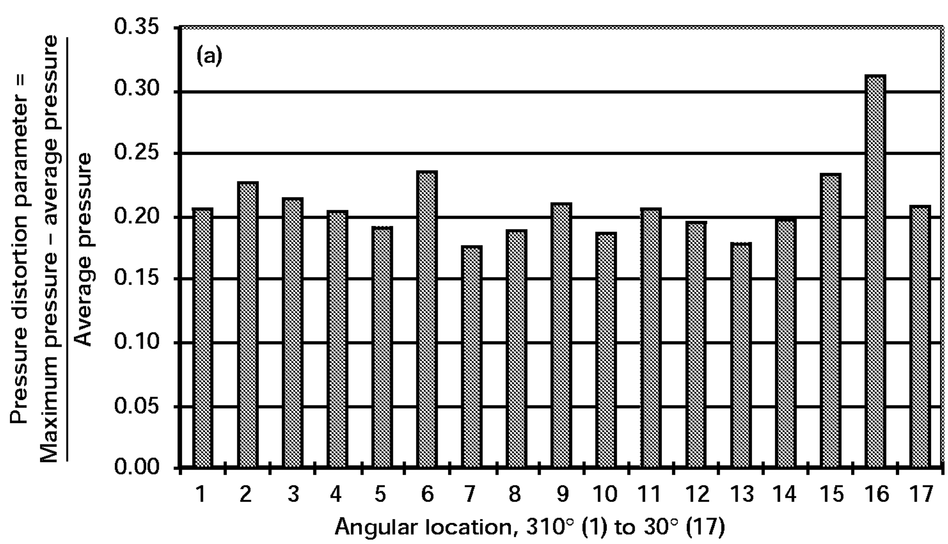


Figure 17.—Plenum insert exit (bellmouth inlet) total pressure profiles during rotation of bellmouth inlet rake in increments of 5°. Inlet temperature, 60 °F; inlet pressure, 11.4 psia. (a) Rotation from 310° (looking forward from aft) to 30°; facility configuration: plenum insert manways closed, plenum bypass open, plenum atmospheric ports closed, plenum insert bypass closed. (b) Rotation from 30° (looking forward from aft) to 305°; facility configuration: plenum insert manways closed, plenum bypass open, plenum atmospheric ports closed, plenum insert bypass open. (c) Rotation from 30° (looking forward from aft) to 315°; facility configuration: plenum insert manways open, plenum bypass open, plenum atmospheric ports open, plenum insert bypass open.

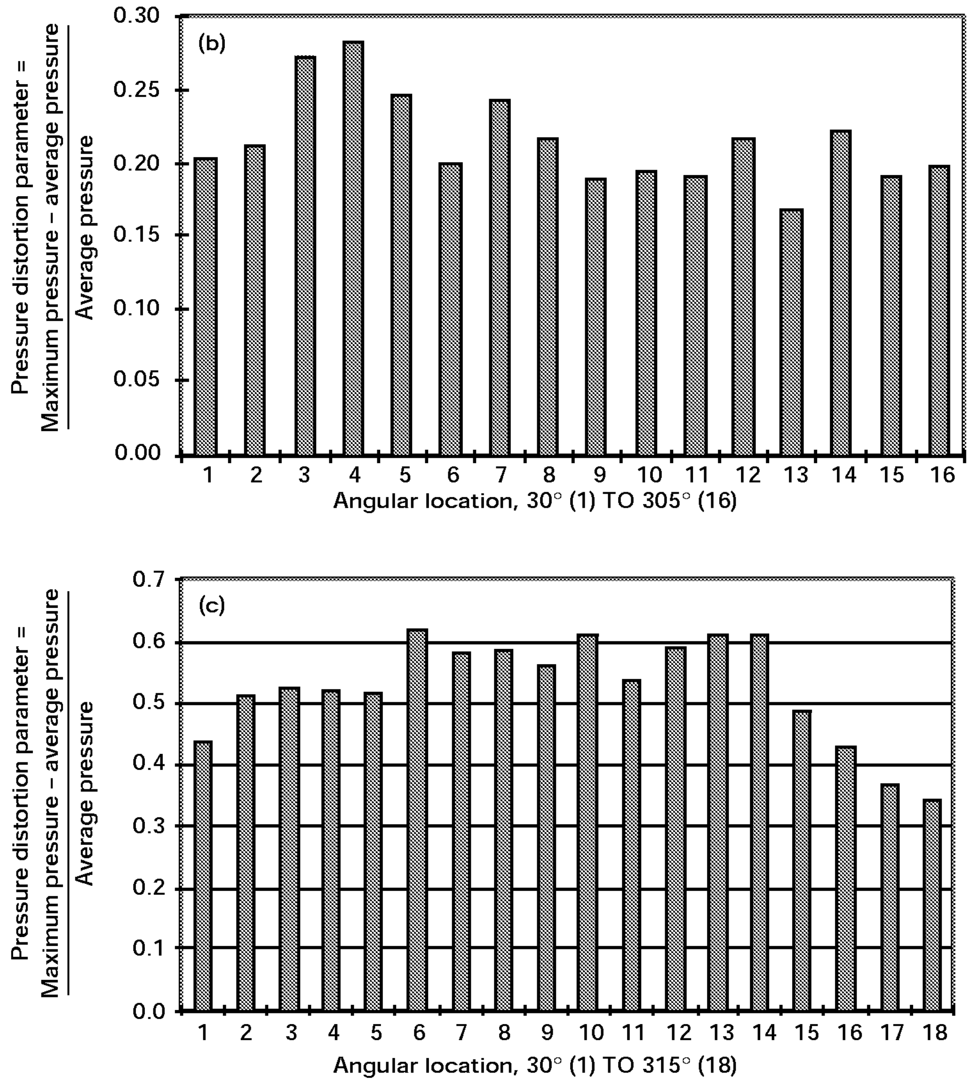


Figure 17.—Concluded. (b) Rotation from 30° (looking forward from aft) to 305°; facility configuration: plenum insert manways closed, plenum bypass open, plenum atmospheric ports closed, plenum insert bypass open. (c) Rotation from 30° (looking forward from aft) to 315°; facility configuration: plenum insert manways open, plenum bypass open, plenum atmospheric ports open, plenum insert bypass open.

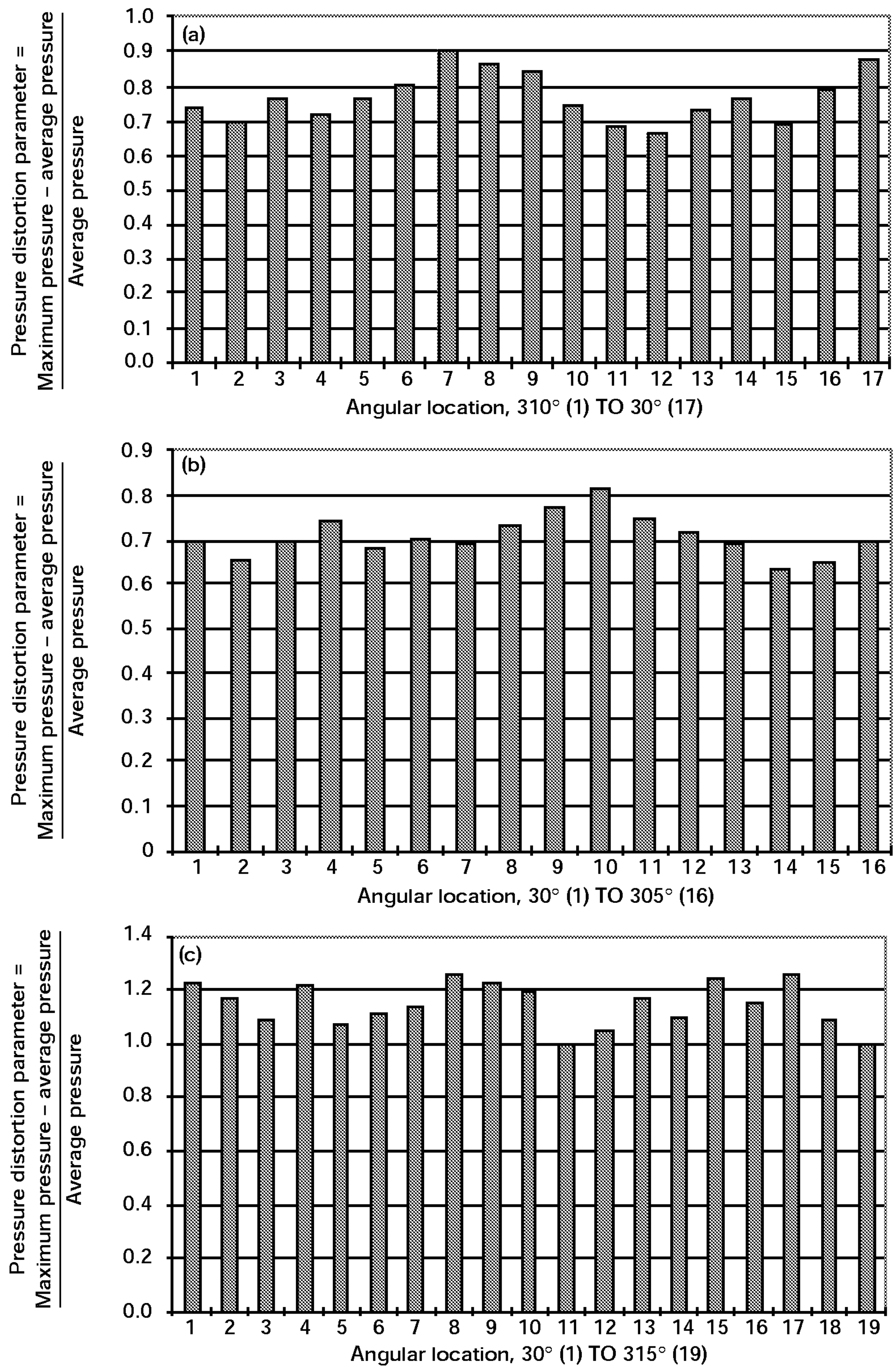
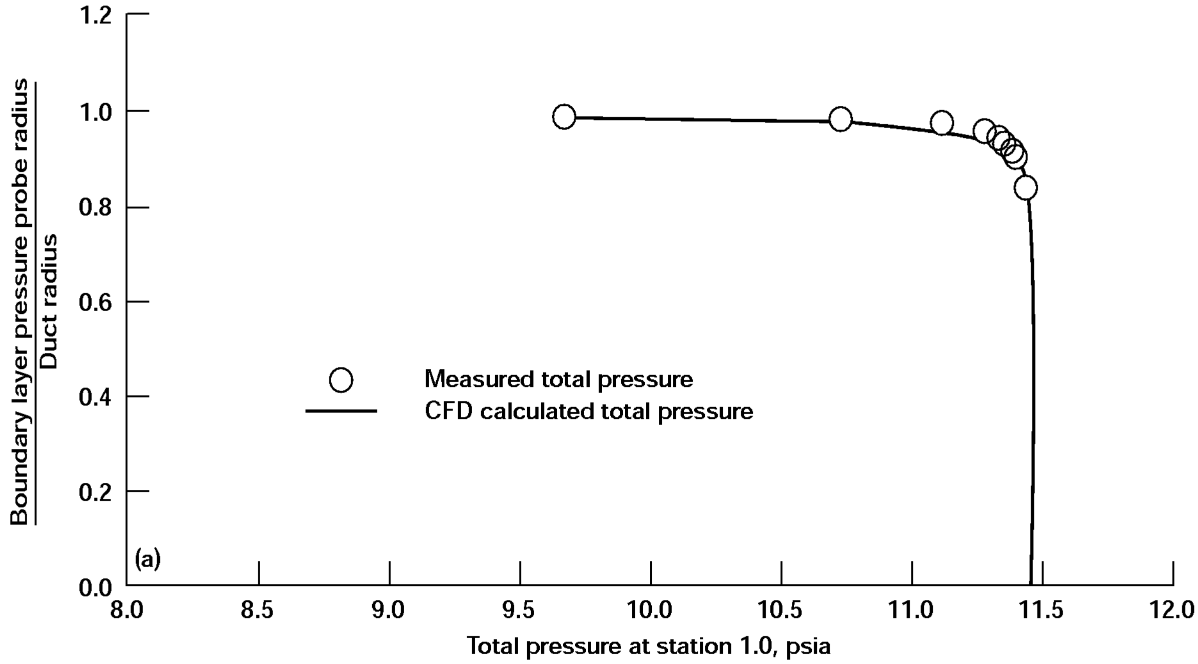


Figure 18.—Cold-pipe inlet total pressure profiles during rotation of total pressure inlet rake in increments of 5°. Inlet temperature, 60 °F; inlet pressure, 11.4 psia. (a) Rotation from 310° (forward looking aft and down) to 30°; facility configuration: plenum insert manways closed, plenum bypass open, plenum atmospheric ports closed, plenum insert bypass closed. (b) Rotation from 30° (forward looking aft and down) to 305°; facility configuration: plenum insert manways closed, plenum bypass open, plenum atmospheric ports closed, plenum insert bypass open. (c) Rotation from 30° (forward looking aft and down) to 315°; facility configuration: plenum insert manways open, plenum bypass open, plenum atmospheric ports open, plenum insert bypass open.



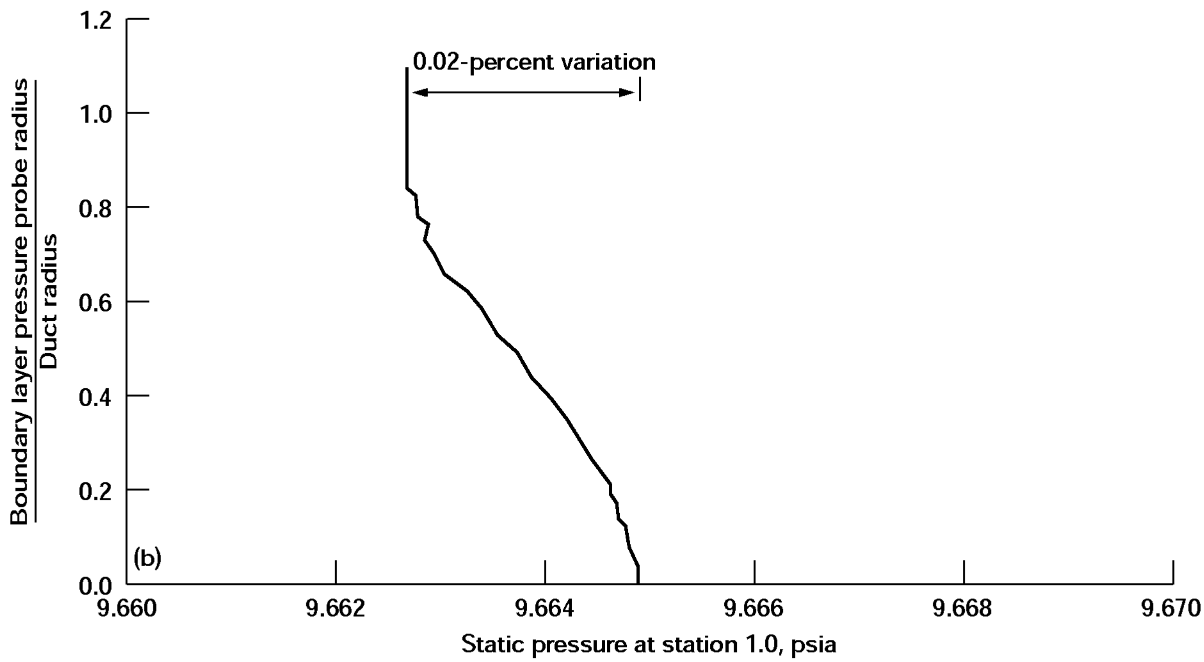


Figure 19.—Airflow measuring station (1.0 in Fig. 8(b)) pressure profiles. Inlet pressure, 11.4; temperature, 60 °F; duct radius, 16.4 in.; airflow, 160 lb/sec; test article configuration, cold pipe with ASME nozzle. (a) Comparison of measured boundary layer total pressure profile and CFD analysis, (b) Radial static pressure profiles from CFD analysis.

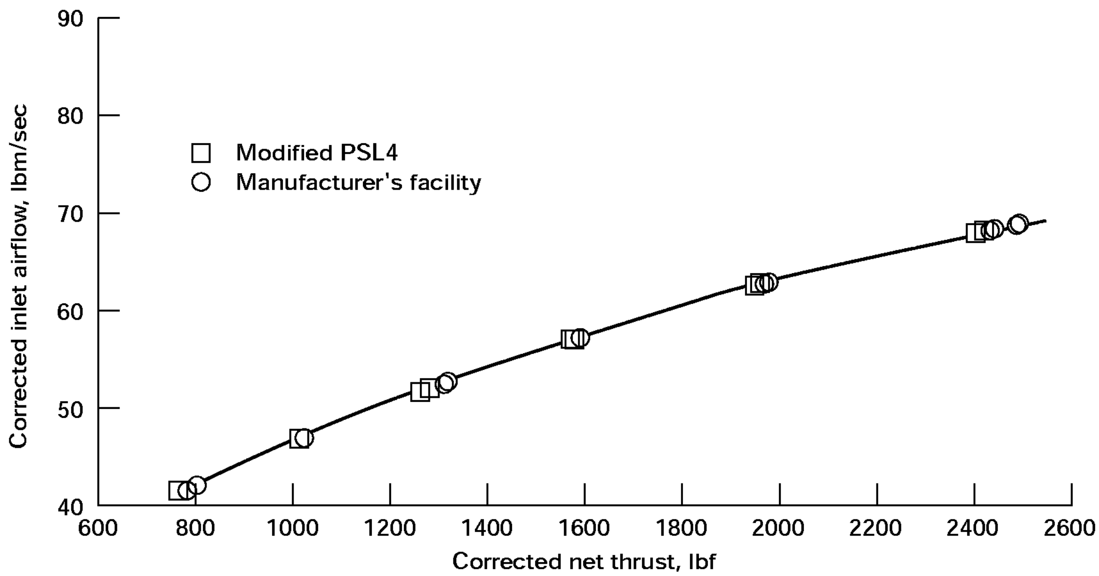


Figure 20.—Comparison of propulsion system performance in modified PSL4 facility and in manufacturer's facility.

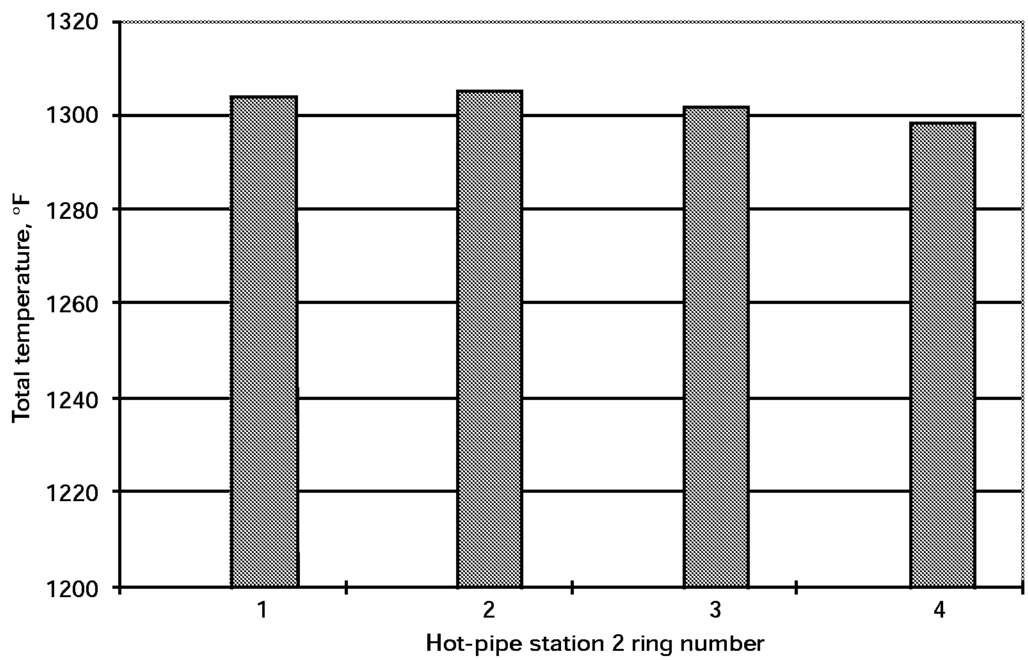


Figure 21.—PSL4 insert exit total temperature profiles during hot-pipe tests. Insert exit pressure, 133 psia; airflow, 159 lb/sec; temperature, 868 °F.

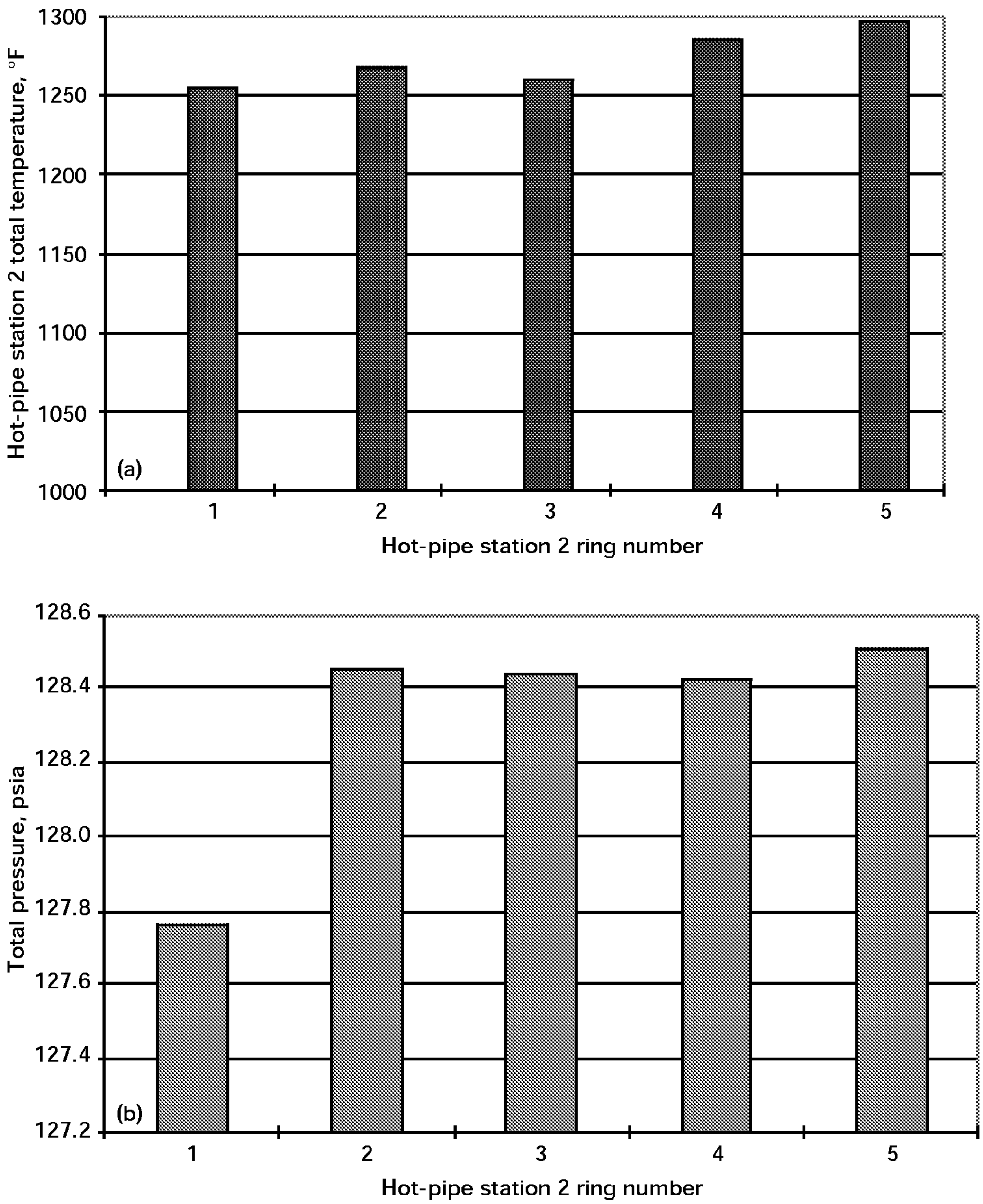


Figure 22.—PSL4 hot-pipe total temperature profiles at station 2 (fig. 10(b)). Insert exit pressure, 133 psia; airflow,159 lb/sec; temperature, 868 °F. (a) Total temperature. (b) Total pressure.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
November 1998

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Design, Installation, and Evaluation of an Altitude Test Facility Modification

5. FUNDING NUMBERS
WU–523–91–13–00

6. AUTHOR(S)
Mahmood Abdelwahab, Allan S. Moore, Ronald H. Soeder,
Richard N. Sorge, Richard DelRoso, and Dennis J. Dicki

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–11016

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM—97-206323

11. SUPPLEMENTARY NOTES
Mahmood Abdelwahab, Allan S. Moore, Ronald H. Soeder, Richard N. Sorge, Richard DelRoso, NASA Lewis Research Center; Dennis J. Dicki, DYNACS, Inc., 2001 Aerospace Parkway, Brook Park, Ohio 44141 (work funded by NASA Contract NAS3–27186). Responsible person, Mahmood Abdelwahab, NASA Lewis Research Center, organization code 7500, (216) 433–3701.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Categories: 05, 07, and 09 Distribution: Nonstandard

This publication is available from the NASA Center for AeroSpace Information, (301) 621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

This report describes the design, installation, and evaluation of the turbine engine altitude test facility modifications. This facility is located in test cell 4 (PSL4) at the Lewis Research Center Propulsion Systems Laboratory (PSL). The modifications were made to enhance the test cell capability for engine inlet air supply conditions from a prior maximum of 55 psia and 600 °F to a new rating of 165 psia and 1200 °F. The maximum conditions reached during the interim evaluation were 129 psia and 844 °F at an airflow of 159 lb/sec. Also, the modified facility airflow quality as defined by the flow characteristics at a typical gas turbine engine inlet were investigated and were adequate.

14. SUBJECT TERMS
Turbine engine altitude test facility; Modification; Design; Installation; Test; Evaluation

15. NUMBER OF PAGES
47

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	